GEOTECHNICAL & FLOODING RECONNAISSANCE OF THE 2014 MARCH FLOOD EVENT POST 2010-2011 CANTERBURY EARTHQUAKE SEQUENCE, NEW ZEALAND

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Photographs on Front Cover: Left Liquefaction severity (Courtesy of Russell Green, Virginia Tech) Right flooding at Gayhurst Road and Gloucester Street, Avonside, Christchurch, NZ (Courtesy of Tonkin & Taylor).

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List of Acronyms

CCC	Christchurch City Council
CER	Canterbury Earthquake Recovery
CERA	Canterbury Earthquake Recovery Authority
CES	Canterbury Earthquake Sequence
CHRP	Canterbury Home Repair Program
CWS	Canterbury Waste Service
CWW	City Water & Waste Unit
EC	Earthquake Commission
ECAN	Environment Canterbury
EQC	Earthquake Commission
FMA	Flood Management Area
GEER	Geotechnical Extreme Event Reconnaissance
GRP	Glass Reinforced Plastic
IFV	Increased Flooding Vulnerability
LGA	Local Government Act
LIM	Land Information Memorandum
NSF	National Science Foundation
NZTA	New Zealand Transport Agency
RMA	Resource Management Act
RRZ	Residential Red Zone
TCLEE	Technical Council on Lifeline Earthquake Engineering
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
UC	University of Canterbury
WS	Water Supply
WW	Waste Water
WWTP	Waste Water Treatment Plant

1. INTRODUCTION

The city of Christchurch is the second largest city in New Zealand located on the South Island in the Canterbury Plain. The city is located in a low-lying and low-gradient coastal flood plain. Portions of Christchurch were historically characterized by marshy, poorly draining land that has been drained to make the land inhabitable. As a result, Christchurch is naturally prone to flooding from several rivers passing through and around the city, high artesian groundwater, and coastal influences. Numerous inundation protection measures have been implemented to control drainage and flooding, which have proven effective over the past several decades for controlling design level flooding.

Christchurch was struck by a sequence of strike-slip and thrust earthquakes in 2010 and 2011; the most significant earthquakes were: M_w 7.1 on September 4, 2010); M_w 6.2 on February 22, 2011, M_w 6.0 June 13, 2011, M_w 5.8 and M_w 5.9 on December 23, 2011. The 2010 earthquake epicenter was located 45 km west of Christchurch while the 2011 earthquakes were about 6 to 10 km from the city center. The 4 September 2010 earthquake is referred to herein as the Darfield earthquake, the 22 February 2014 earthquake is referred to herein as the Christchurch earthquake, and collectively all these earthquakes are referred to as the Canterbury earthquake sequence. There were significant seismic-induced geotechnical mechanisms important to increasing the flood susceptibility in Christchurch, including vertical tectonic movements, liquefaction induced settlement, and lateral spreading. Liquefaction and lateral spreading, in addition to sedimentation, were significant in reducing river channel capacity. The local geomorphology and ecological systems have been modified from these geotechnical earthquake effects and influence the flood risks. Additional non-geotechnical mechanisms significantly effected overland and river channel flow including earthquake-induced damage to existing flood protection and drainage infrastructures, the stormwater drainage system, and other key infrastructures conveying water including the surface roads.

On March 4th to 5^{th,} 2014, a 992 hPa tropical depression sat east of the Canterbury coast for several days, providing heavy and sustained rainfall over Christchurch. This was the heaviest rainfall in the city since the 1970s. At the same time coastal water levels were also high; a high tide meeting a 20 to 50% annual exceedance probability level existed at the time of the storm event, which was compounded by a storm surge associated with the low-pressure weather system. This combination of heavy sustained rainfall, high tide, and storm surge resulted in flooding. Although, Christchurch is susceptible to flooding from this type of event, the above-described earthquake impacts, along with post-earthquake construction activities creating obstructions in the watercourses, were found to contribute to the documented flooding. In some areas flooding occurred mostly as a result of the earthquake impacts, while other locations were pre-exposed to flooding in this event but the earthquake impacts contributed to increase the inundation depth and area.

This report presents an overview of the earthquake-induced changes that were observed to have affected the city's response to flood events. Following this Chapter 1 introduction, the second chapter presents a historical perspective of flooding and threats to Christchurch and an overview of the 5 March, 2014 flood event. Chapter 3 describes land deformations resulting from the Canterbury earthquake sequence and descriptions on how these deformations related to increased flood risk in The detailed effects of the 2010-2011 Canterbury earthquake sequence were presented in two previous GEER reports:

http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Christchurch_2011/Index_Christchurch_2011.html

http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Darfield%20New%20Zealand_ 2010/Cover_Darfield_2010.html

Flood modelling for pre- and post-earthquake sequence conditions are examined and compared in Chapter 4 and correlated with actual flood conditions. The effects of earthquake-induced damages are described in Chapter 5. Chapter 6 describes the post-flood geotechnical field investigations and observations and Chapter 7 describes the post-flood impacts on lifeline systems. The flood impacts on the built environment are summarized in Chapter 8. Finally, the role of government entities and future flood management policies are considered in Chapter 9.

Shortly after the Canterbury earthquake sequence the University of Canterbury (UC) worked with the American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering (TCLEE) to develop an earthquake-flood multihazard project to investigate the increased flood risk to Christchurch. The UC-TCLEE international collaboration project on "Earthquake-Flood Multihazard Impacts to Lifeline Systems" was formalized in 2012. UC students and advisors were working with the Christchurch lifeline organizations and community when the 5th March 2014 floods occurred. The GEER team mobilized to investigate and document the flood events, in support of initiatives such as the UC-TCLEE on-going earthquake-flood multihazard investigation efforts.

The flood events occurring after the 2010-2011 Canterbury earthquake sequence present a unique opportunity to investigate multihazard events and their impacts on lifelines in a real-time reconstruction setting. Following the March 5th flood event, the GEER team was mobilized to assist ongoing research at UC by conducting a geotechnical reconnaissance through a joint USA-NZ team, with the main funding for the USA contingent coming from GEER. The majority of the observations presented in this report resulted from reconnaissance efforts over a period of four days (18-21 March 2014). However, members of the NZ contingent and one member of the USA contingent have also been working on data collection related to multihazard events in Christchurch for several years following the Canterbury earthquake sequence.

The team for the 5th March 2014 flood event reconnaissance included the following members:

- Mr. John Allen (TRI/Environmental, Inc., Austin, TX, USA)
- Dr. Sarah Beaven (University of Canterbury, Christchurch, New Zealand)
- Dr. Tom Cochrane (University of Canterbury, Christchurch, New Zealand)
- Dr. Craig Davis (City of Los Angeles Department of Water and Power, Los Angeles, CA, USA)
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The USA GEER and New Zealand members worked as one team, sharing resources, information and logistics in order to conduct a thorough and efficient reconnaissance covering large areas of the wider Christchurch city over a limited time period. The results of this effort are intended to feed into the on-going efforts to reduce the post-earthquake flood risks in Christchurch, New Zealand, at the same time as elucidating the reality of multihazard risks that communities worldwide may be exposed to flowing significant earthquake events. This report summarizes the key evidence and findings from the reconnaissance efforts. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the individual or collective authors and editors, and do not necessarily reflect the views of the associated organizations and funding agencies.

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Invaluable support and contributions for our efforts was provided through data/information sharing. Dr. Sjoerd van Ballegooy and Mark Taylor, from Tonkin and Taylor, Christchurch, provided valuable information related to liquefaction-induced land and flood damage to the residential properties. Dr. Marion Gadsby and the team at ECAN provided valuable support and information related to groundwater and pre-earthquake flood modelling. Graham Harrington and the team at CCC (Christchurch City Council, New Zealand) provided valuable support and information on pre-earthquake flood modelling and post-earthquake conditions influencing flooding in Christchurch.

We are deeply grateful to all the interviewed persons and all the experts who provided information, data and who reviewed the report.

We are sincerely grateful to Prof. Jonathan Bray, from University of California, Berkeley who promoted as chair of the GEER Association, this reconnaissance and who provided, together with Prof. Misko Cubrinovski, from University of Canterbury, constant encouragement and guidance.

2. HISTORY OF FLOODING IN CHRISTCHURCH

The city of Christchurch is located on the predominantly low-lying and low-gradient coastal portion of the Waimakariri River flood plain. This plain was constructed of sediments from various sources including the Waimakariri River, the Canterbury continental shelf and other sediments deposited through coastal processes (Figure 2-1). When Christchurch was founded in the mid-nineteenth century, the area now occupied by the eastern suburbs was characterized by marshy, poorly draining land. To make the land habitable, the Provincial Government and city authorities attempted to improve the land drainage, with extensive drainage achieved after formation of the Drainage Board in the mid-1870s.

Christchurch City has numerous flooding threats including the local rivers, tidal influences and storm surges. The Waimakariri River to the north represents the most potentially disastrous threat while the local rivers within the city represent spatially less-extensive but temporally more frequent flooding threats. The Waimakariri River is a dynamic braided river that, over geological time, is prone to avulsing and travelling across the flood plain, having travelled as far south as Te Waihora Lake Ellesmere during the late Holocene (Figure 2-1). Smaller waterways are located throughout the city, including the Styx, Avon, Halswell and Heathcote Rivers (Figure 2-2). This section describes the historical flooding by the Waimakariri and the smaller rivers of the city.



Figure 2-1 Christchurch City is bounded to the north by the Waimakariri River and to the south by the extinct volcanic complex of Banks Peninsula.



Figure 2-2 The urban rivers and waterways of Christchurch city, including the Styx, Avon, Halswell and Heathcote Rivers and the Avon-Heathcote Estuary/ Ihutai.

Flooding from the Waimakariri River

Originating in the Southern Alps and currently flowing to the north of Christchurch city, the Waimakariri is a steep, dynamic, gravel-bed, braided river which has historically been prone to leave its banks during large floods but which is now constrained between engineered stop-banks. Major floods in the Waimakariri River are generated from heavy rainfall in the mountainous, upper part of the catchment. Flooding from the Waimakariri is considered a major threat to Christchurch and the nearby towns due to the size of the floods generated by the river. The Waimakariri Rivier has a catchment area of 3,990 km², a low flow of about 25 cumecs (883 cusecs), mean flow of 120 cumecs (4238 cusecs), a 450 year return period flows of 4,700 cumecs (165979 cusecs), with the largest recorded floods in December 1957 reaching 3,990 cumecs (140906 cusecs) (where 1 cusecs = 35.31 m^3 /s). Potential damage from the worst case scenario flood or Probable Maximum flood is estimated at approximately NZ\$5 billion (van Kalken, et al., 2007).

Post settlement of the Canterbury region, flood waters from the Waimakariri River entered Christchurch City numerous times: in 1858, 1859, 1865, 1866, and 1868. Following these

floods, there were efforts to stabilize the river to protect settlements from flooding, particularly from the southern part of the river towards Christchurch. Engineering efforts, including stopbanks, were not successful in preventing major floods in 1940 and 1950. The last time the Waimakariri left its present location and flowed through Christchurch city was 1957. In response to these floods, a new river modification scheme was developed in 1960 to raise and strengthen existing stop banks and add additional features such as erosion protection. In more recent years, a secondary stopbank has been designed. This secondary stopbank includes protection for up to a 1 in 10,000 year return period event (van Kalken, et al., 2007).

The stopbanks along the Waimakariri River were damaged during the 2010-2011 Canterbury earthquake sequence and have subsequently been repaired. Damage to the stopbanks is detailed in the previous two GEER reports related to these events (GEER Association Reports No. GEER-024 and GEER-027).

Christchurch City Rivers

The three main rivers within the city of Christchurch are the Styx, Avon, and Heathcote Rivers. Along the eastern edge of the city is the Halswell River which drains to Te Waihora Lake Ellesmere. The three main urban rivers are spring fed and run through populated areas of the city (Figure 2-3). The flat and low-lying areas surrounding these rivers have been prone to periodic flooding throughout the city's history. Additionally, the city's development and growth has contributed to increased runoff and flooding from these rivers. Floods from these rivers are typically generated by moderate-intensity, long-duration rain storms (Christchurch City Council, 2003).

The Styx River, to the north, has experienced floods and flooding exacerbated by tidal inundation. Commissioned in the mid-1980s, tide-gates have been installed on the Styx Figure 2-4) to limit tidal effects upstream and to protect the floodplains near the stopbanks of the Waimakariri River to the north (Taylor, 2005).



Figure 2-3 Major catchments in Christchurch City (Tonkin and Taylor, 2013).



Figure 2-4 Tide-gates on the Styx River at Brooklands (Christchurch City Council, 2012).

In the Avon River basin, over 30 floods since 1883 have been documented and have caused damage ranging from stormwater ponding to river breakouts. In July 1955, March 1957 and August 1992, high tides exacerbated the flooding. Flood control measures, including stopbanks, are installed along the lower Avon to protect property from flood damage. The performance of these stopbanks is detailed in Chapter 6 of this report. Following the 2010-2011 earthquake sequence, the suburb of Avonside experienced extensive subsidence. As a result, the stopbanks were increased in height by up to 1 meter in some places (Figure 2-5).

The Flockton area or Dudley Creek basin, a sub-catchment of the wider Avon River basin, experiences frequent flooding. The Flockton area has experienced numerous flood events from Dudley Creek (Figure 2-6), which is a tributary of the Avon River. This area was flooded in August 2012, June 2013 and March 2014. Prior to the earthquake sequence, this area was prone to flooding, but the frequency and magnitude of flooding seems to have increased since the earthquakes. To alleviate flooding, a pump was installed to move the flood waters. Figure 2-7 shows the 50 year flood levels in the Flockton area before and after the earthquake sequence. As demonstrated by comparisons between Figures 2-7a and 2-7b, there are much larger areas potentially subject to flooding after the earthquake sequence as compared to before the earthquakes – shown as the larger extent of the areas colored orange to red to indicate deeper flood waters.



Figure 2-5 Stopbank along the Avon River on Avonside Drive (-43.503590°, 172.683632°).



Figure 2-6 Bridge over Dudley Creek (-43°30' 40.41" S, 172°39'18.52"E) along Stapletons Road.





(0)

Figure 2-7 50 year flood levels in the Flockton area: (a) before, and (b) after the earthquake sequence (Christchurch City Council, 2014).



Figure 2-8 Barrage on the Woolston Cut section of the lower Heathcote River (-43°33' 11.72"S, 172°41'07.33"E).

The Cranford basin comprises a local depression in Christchurch that is a natural flood ponding area draining to both the Styx and the Avon basins. The basin is approximately 89 hectares and is frequently inundated. The basin was flooded in the March 4-5, 2014 event. The Christchurch City Council is considering the purchase of this land to establish it as a local drainage reserve (Christchurch City Council, 2012).

Similar to the Styx and Avon, the Heathcote River has had numerous floods. In 1941, the Woolston Cut was added in an attempt at river flood mitigation. However, this straightening of a lower river channel reach allowed saltwater to flow more readily back up the river. A barrage was added to prevent the saltwater backup Figure 2-8. Prior to the earthquake sequence floodwaters reached heights above house floor levels in the Heathcote River basins in 1968, 1975, 1977 and 1980 (Christchurch City Council, 2003).

March 4-5, 2014 Flood

During the period of March 4th to 5^{th,} 2014, a 992 hPa tropical depression sat east of the Canterbury coast for several days, providing heavy and sustained rainfall over the wider city. Rain gauges recorded a high degree of spatial variation in total precipitation across the city, with gauges measuring values of 78 mm at Lower Styx Road, 160.8 mm at the Botanical Gardens, to 341.2 mm towards Akaroa, a settlement that lies south of the city and on the south-side of Banks Penninsula (Table 2-1). The precipitation amounts correspond to events with annual return periods ranging from 1-in-20 to 1-in-100 (Tonkin & Taylor, 2014). The most significant damage occurred in the communities along the Avon and Heathcote Rivers, the two main rivers that drain the eastern, coastal half of the city.

At the same time as the large rainfall event occurred, coastal water levels were also high. There was a storm surge associated with the low pressure weather system that produced the flooding. Tonkin & Taylor (2014) estimates the storm surge at a maximum of between 0.3 and 0.4 m. Adding to this, there was a tide of 20-50% annual exceedance probability (1-in-5 to 1-in-2 return period). This large tide is referred to as a perigean spring tide or king tide.

Table 2-1 Rainfall levels recorded by Christchurch City Council gauges from 3-6 March 2014 (provided by Tonkin and Taylor, 2014)

Site	Basin	Rainfall Depth (mm)
Site 324607 Lower Styx Rd	Styx	78
Site 324608 PS62, Tyrone Street	Styx	76.2
Site 324610 Firestone Factory, Papanui	Avon	139.6
Site 325403 PS80, Templeton		82.4
Site 325507 College of Education, Ilam	Avon	120.8
Site 325510 Halswell Retention Basin	Halswell	106
Site 325512 Aidanfield, Dunbars Reservoir		107.2
Site 325616 Christchurch Botanical Gardens	Avon	160.8
Site 325617 Horseshoe Lake, PS205	Avon	133.2
Site 325618 PS42, Sparks Road	Halswell	141.8
Site 325619 Tunnel Road, Heathcote	Heathcote	150.6
Site 325621 Bowenvale Flume	Heathcote	180.2
Site 325711 Van Asch St. Sumner	Sumner	180
Site 325712 Reservoir No.4, Clifton Tce	Sumner	189
Site 325716 Ocean outfall, Sth Brighton		133
Site 326616 Upper Bowenvale Valley	Heathcote	297.6
Site 325615 Kyle St EWS		152.4
Site 327804 4960 Chch-Akaroa Hwy		341.2

The variability in the precipitation spatial distribution led to localized flooding rather than widespread flooding (Figure 2-9). The Waimakariri River did not experience flooding and the stopbanks performed as expected. Locally, in Christchurch, flooding was experienced along the Avon River (Figure 2-11 through Figure 2-15), most notably, Dudley Creek, and the Heathcote River as well as localized stormwater ponding (Figure 2-15).

The area that experienced the greatest flooding in this event is an area called Flockton. The Flockton area along Dudley Creek and the Avon River has experienced historical flooding. Due to the 2010-2011 earthquake sequence, ground subsidence has occurred in this area, making it more susceptible to flooding. Additionally, there was silting of the creek and lateral spreading that narrowed the channels, reducing their hydraulic capacity; these topics are discussed in detail

in Chapters 3 and 5. Figure 2-10 is a schematic of the area that demonstrates the 50 year flow against the existing channel capacity (Christchurch City Council, 2014).

Similar to the Avon, the Heathcote also experienced flooding (Figure 2-16 through Figure 2-18). The photos provided from Tonkin and Taylor begin at the top of the basin and proceed towards the ocean. The upper part of the basin had ponding (Figure 2-16). This area has been identified by the Christchurch City Council as a natural ponding basin and has been left without development to capture flood waters. Figures 2-11 to 2-18 present photographs showing flood waters within the City of Christchurch. The Mayoral Task Force (Christchurch City Council, 2014) report provides more detailed descriptions of local flood impacts and temporary defense measures and the later chapters in this report summarize flood effects on geotechnical and lifeline systems.



Figure 2-9 Observed flooding in Christchurch in March 2014 with general location of the (A) Cranford Basin and (B) Flockton area compared to hindcast model predictions (Tonkin & Taylor, 2014).



Figure 2-10 Flockton area channel capacity shown with 50 year flows in the arrows and current channel capacities in red (Christchurch City Council, 2014).



Figure 2-11 Lower Avon River at New Brighton Road (-43°30'02.52"S, 172°41'03.65"E). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-12 Avon River at Gayhurst Road (43°31'17.58"S, 172°, 40'21.96"E). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-13 Localized flooding at the intersection of Prestwick Street and Avonside Drive (-43.503590°, 172.683632°). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-14 Flockton area from Woodville Street (43°30'33.65 S", 172°39'00.65"E). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-15 Localized flooding in Manning Place & Wilberry Street (43°32'41.63 S", 172°39'58.28"E). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-16 Heathcote River off Worsley Road (-43.580827°, 172.616142°). Photo courtesy of Tonkin & Taylor 2014.



Figure 2-17 Heathcote River Waimea Tce (43°34'08.59' S, 172°38'22.22" E). Photo courtesy of Tonkin & Taylor 2014.





(a)

(b)

Figure 2-18 Heathcote River off Centaurus Road illustrating (a) flooding on March 5, 2014 (Credit: Tonkin & Taylor 2014) and (b) normal flow during GEER visit March 19, 2014. (43°34'01.69"S, 172°38'45.85"E).

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3. POST EARTHQUAKE SEQUENCE LAND DEFORMATION

Land damage from the four largest earthquakes in the 2010-2011 Canterbury earthquake sequence (CES) have been well documented in previous GEER reports and by numerous researchers (e.g., Quigley et al., 2010; Quigley et al. 2013; Cubrinovski et al., 2014; Green et al., 2014; Maurer et al., 2014; van Ballegooy et al., 2014). The effects of tectonic uplift, liquefaction induced settlement, sedimentation of river channels from ejected material and lateral spreading has resulted in land damage and influenced river morphology within Christchurch. The GEER team specifically investigated the related land damage mechanisms and their impacts on the March 5th flood event. The impacts of the land damage and changes in the river are summarized in this section.

Tectonic uplift and earthquake shaking

Earthquake frequency-magnitude distributions during the CES are summarized in Figure 3-1 and Figure 3-2 (Li et al., 2013; Bradley et al., 2014; Quigley et al., in review). The eight largest earthquakes by magnitude include the 4 September 2010 (Mw=7.1), 22 February 2011 (three earthquakes: Mw=6.2, 5.5, 5.6), 13 June 2011 (two earthquakes: Mw=5.3, 6.0) and 23 December 2011 (two earthquakes: Mw=5.8, 5.9). Figure 3-1B shows how all of these earthquakes were accompanied by an increase in aftershock frequency (Figure 3-1B). Figure 3-3 presents the magnitudes weighted (to Mw7.5) peak ground accelerations (PGA7.5). As seen in Figure 3-3, all of the Mw \geq 5.8 events, and the Mw 5.3 June event, caused ground shaking in eastern and southern Christchurch with PGA7.5 $\geq 0.10g$, and caused significant liquefaction damage, as indicated by the formation of sand blows and lateral spreading cracks in the most susceptible parts of eastern Christchurch (e.g., Quigley et al., 2013). Spatially localized, minor liquefaction was also reported in isolated areas following the 19 Oct 2010 Mw 4.8 (Green et al., 2010), 16 April 2011 Mw 5.0, and 21 June 2011 Mw 5.2 earthquakes (Quigley et al., 2013), although these events did not cause significant land damage and are thus unlikely to have contributed to increased flood hazard. The locations of major faults involved in the CES are shown in Figure 3-2. For detailed reviews of the geologic and seismic aspects of the CES see Quigley et al. (2010, 2012, 2013); Beavan et al. (2010, 2011, 2012), Kaiser et al. (2011); Duffy et al. (2012), Bradley et al. (2014); and Hughes et al. (in review). No pre-CES regional earthquakes since 1940 are likely to have been of sufficient magnitude and shaking intensity to induce liquefaction and impact on flood hazard (Figure 3-1A). A local earthquake (Mw 4.7-4.9) in 1869 caused pervasive damage in parts of Christchurch consistent with $PGA \ge 0.2$ g shaking and may have induced tidal changes in the Heathcote River, as reported in the Weekly News 26 June 1869 (cited in Downes and Yetton, 2012).

Vertical tectonic surface displacements of 0.8 to 1.8 m along the Greendale Fault approximately 50 km west of Christchurch caused partial avulsion of the Hororata River shown in Figure 3-2

and related flooding (Duffy et al., 2013) during the 4 Sept 2010 earthquake. However, vertical deformations in Christchurch (excluding the effects of lateral spreading and liquefaction) in this event were < 2-5 cm (Beavan et al., 2010, 2012) and thus did not contribution significantly to flood hazard.



Figure 3-1 Seismicity of the Canterbury earthquake sequence (CES). A) Gutenburg-Richter frequency-magnitude plot comparing CES seismicity with seismicity in the same region over a 60 year period prior to the CES. The low earthquake frequency and magnitudes prior to the CES suggests that regional earthquakes over this time period are unlikely to have contributed to flood hazard via seismic shaking. See text for additional details. B) CES earthquakes plotted against time, showing increase in seismicity rate immediately following larger (e.g., $Mw \ge 5.5$) events and decay of seismicity rates following these events (inset).



Figure 3-2 Location of active faults that ruptured in the CES and related spatial distribution of Richter magnitude (ML) \geq 3.0 earthquakes. Focal mechanisms for major events as shown. Of the estimated 12 to 14 major faults that ruptured in the CES, only two faults (Greendale Faults east/central and west) caused surface rupture; the rest of the faults were blind.

The 22 February 2011 Mw 6.2 Christchurch earthquake involved the rupture of 2 to 3 blind faults, shown in Figure 3-2 and Figure 3-4, with reverse and right-lateral displacements (Beavan et al. 2012). The inferred rupture reached as shallow as ~0.5 km depth below the surface, suggesting rupture termination in Miocene volcanic rocks. Maximum coseismic slip was 2.5 to 3 m at depths of 4-6 km (Beavan et al. 2012). Constraints on surface deformation above the fault ruptures are provided by continuous GPS (cGPS), geodetic 'campaign' GPS, differential Interformetric Synthetic Aperture Radar (InSAR), and differential Light Detection and Ranging (LiDAR) data. Maximum vertical displacements recorded by cGPS in the Christchurch earthquake were -51 mm at TNZ (Figure 3-4A); no cGPS vertical displacements in the other earthquakes exceeded 10 mm (Beavan et al., 2012) and thus this data is not considered further. Maximum 22 February earthquake vertical displacements recorded by campaign GPS data include 535 mm uplift near the Avon Heathcote Estuary (open star in Figure 3-4A) and numerous locations with ≥ 100 mm of subsidence (Figure 3-4A); Beavan et al. (2011) cautioned that large errors may be associated with some of these data. Differential InSAR reveals large (> 6-10 km²) areas of \geq 30 cm displacement towards and away from satellite look directions (Beavan et al., 2011) that reflect both horizontal and vertical displacements resulting from tectonic and shaking induced deformation. Differential LiDAR reveals areas of vertical uplift

that exceed 30-40 cm and large areas of subsidence of >10-50 cm (Hughes et al., in review). Vertical uplift primarily reflects tectonic displacement on the underlying faults, while subsidence records differential settlement, lateral spreading and other types of ground failure in addition to tectonic displacement variations.



Figure 3-3 Relationship of magnitude-weighted PGA7.5 and Mw for largest CES earthquakes that did and did not create surface evidence for liquefaction at a selected study site adjacent to the Avon River in eastern Christchurch. PGA7.5 thresholds for inducing major liquefaction and lateral spreading at this site are 0.10 g, although surface features were created at shaking intensities as low as ≤ 0.06 g. A shaking threshold ≥ 0.1 g PGA7.5 for inducing land damage and influencing channel morphology, flood plain elevations, and consequently flood hazard at high susceptibility sites is likely. Figure from Quigley et al. (2013).

The 13 June 2011 Mw 6.0 earthquake likely involved an intersecting ENE-striking reverse-right lateral fault and NW-striking left-lateral fault, shown in Figure 3-4B with ~ 1 km deep rupture extent and maximum subsurface slip of < 1 m (Beavan et al. 2012). Maximum campaign GPS recorded uplift exceeded 13 cm (open star in Figure 3-4B) and several locations in eastern Christchurch (see closed stars in Figure 3-4B for examples) recorded subsidence > 10 cm (Beavan et al., 2012). Differential InSAR reveals areas where combined differential vertical and horizontal movements exceeded 10 cm (Beavan et al., 2012) and differential LiDAR reveals large areas of eastern Christchurch that subsided \geq 10-20 cm.

The 23 December 2011 Mw 5.8 and Mw 5.9 earthquakes ruptured NE-striking reverse-rightlateral, blind faults primarily located offshore, shown in Figure 3-4B, with maximum slip of >1.4 m occurring at depths of 2-5 km and rupture extents of ~ 1 km depth (Beavan et al. 2012). Maximum campaign GPS recorded uplift of approximately 10 cm occurred along the eastern coast of Christchurch (open circle in Figure 3-4B); maximum subsidence occurred 5 to 8 km north of uplifted areas (closed circle in Figure 3-4B) (Beavan et al. 2012). Differential InSAR reveals areas where combined differential vertical and horizontal movements exceeded 5 cm (Beavan et al., 2012). Differential LiDAR reveals continued subsidence exceeding 5 to 10 cm in eastern Christchurch.



Figure 3-4 A) Vertical surface displacements in the 22 Feb Mw 6.2 Christchurch earthquake recorded by campaign GPS measurements ('observed') and modelled displacements from fault source models ('modelled') from Beavan et al. (2011). Contours of modelled vertical displacements shown in 50 mm increments. Location of cGPS station TNZ as shown. Site with maximum vertical uplift shown by open star. B) Tectonic component of cumulative vertical displacements (ΔE_{Tec}) in Christchurch and offshore, derived from fault source models of Beavan et al. (2012). The shaking-induced components of vertical deformation are not shown (see Figure 3-5). Up-dip surface projections of faults that ruptured in the 22 Feb (i), 13 June (ii), and Dec 23 (iii) earthquakes shown by dashed lines. See text for details.

The tectonic component of total measured vertical and horizontal displacements was derived from the fault source models of Beavan et al. (2012) (Figure 3-4A); van Ballegooy et al. (2014) used these models to extract the tectonic component in order to document the shaking-induced component of total subsidence (see next section). Hughes et al. (in review) combined the fault source models of Beavan et al. (2012) to produce a composite map showing the cumulative tectonic component of vertical displacements throughout the CES (Figure 3-4B). Three key observations can be made from this modeled displacement field in terms of potential tectonic influence on flooding in Christchurch: (1) The Avon River (AR; Figure 3-4B) has been influenced by cumulative tectonic subsidence throughout its reach, until it crosses the up-dip surface projection of one of the 22 Feb 2011 fault ruptures (Fault i; Figure 3-4B) where it enters the Avon-Heathcote Estuary (AHE in Figure 3-4B), (2) The Heathcote River (HR; Figure 3-4B) has been influenced by cumulative tectonic subsidence in its upstream reach and cumulative tectonic uplift in its downstream reach, with a change across the up-dip surface projection of another one of the 22 Feb 2011 fault ruptures (Fault i; Figure 3-4B), (3) The Avon-Heathcote Estuary (AHE) has been largely influenced by cumulative tectonic uplift throughout its spatial extent. The associated tectonically-induced gradient changes on the Heathcote River are expected to increase flooding in the upstream reach, the tectonic uplift of the AHE is expected to increase flooding in both the Avon and Heathcote Rivers, and the tectonic influence on the Avon River is expected to lower the channel with respect to sea-level, and thus increased flood potential along the river.

Liquefaction induced settlement & lateral spreading

Liquefaction induced settlement was documented in Christchurch and the surrounding communities after the four events making up the 2010-2011 Canterbury earthquake sequence. Pre 2010 to post December 2011, elevation changes for the city were documented by Tonkin & Taylor (2013). Figure 3-5 shows cumulative settlements as a result of the four events in the Avon and Heathcote catchment areas. Cumulative settlements in excess of 1 m can be found within the Avon River catchment area. In the Heathcote catchment area both settlements and uplift of ≤ 0.3 m can be found. Van Ballegooy et al. (2014) found that > 87% of the settlement in Christchurch was associated with ejected soil.

GEER team members classified the ejected material as non-plastic fine sands and silty sands, during the Darfield Earthquake reconnaissance (NZ-GEER, 2010). Much of the silts and sands ejected due to liquefaction in the city were cleaned up after each of the events and placed in stock piles near the Bromley oxidation ponds and at the Burwood Landfill (NZ-GEER, 2011). Evidence of ejected material, as shown in Figure 3-6 was still found in Dudley Creek and along the banks of the Heathcote River near the high water marks during the GEER visit. CCC's Land Drainage Recovery Programme (2014) identified sediment volumes in excess of 350 truckloads have been removed since June of 2013 in ongoing attempts to restore channel morphology, and thus, flow capacity.

Lateral spreading damage within Christchurch was also documented in the previous two GEER reports (NZ-GEER 2010; NZ-GEER 2011) and subsequent publications, and is outside the scope of this report. Horizontal movement towards the center of the channel due to lateral spreading was documented throughout Christchurch and its surrounding communities in the previous GEER reports. This type of ground movement reduced the channel capacities and increased flood risk. Extensive mapping of the lateral spreading throughout the city was later conducted and presented by Tonkin & Taylor (2013). Figure 3-7 shows the mapped lateral spreading along the Avon River and resulting horizontal land movement.



Figure 3-5 Cumulative elevation change along the Avon and Heathcote Rivers pre-2010 and post June/December 2011; (a) Avon Catchment and (b) Heathcote catchment. Maps (a) and (b) have different scales. (Tonkin & Taylor Ltd, 2013, Figure A10)



Figure 3-6 (a) Traces of ejected sand in Dudley Creek (Stapletons Rd: -43.511154°, 172.655033°) and (b) similar sediments deposited during the March 5^{th} Heathcote flooding (Centaurus Rd: -43.567442°, 172.645985°).



Figure 3-7 Lateral spreading and horizontal movement along the Avon River pre 2010 and post June/December 2011earthquakes (Tonkin & Taylor Ltd, 2013, Appendix M Figure 13)







Figure 3-8 (a) Displacement of the river bank towards the center of the river at the Anzac Bridge and (b) example of lateral spread and slumping of bridge abutments creating loss of channel capacity from Cubrinovski et al. (2014)

Cubrinovski et al. (2014) show the collapse of the river banks in Figure 3-8a due to lateral spreading around the bridge foundations along the Avon River. The result is shown in Figure 3-8b as a narrowing of the channel from slumping of the sides and heave at the center as the two slumping sides come together.

Impacts and changes to river morphology

During the GEER team visits after the earthquakes in 2010 and 2011, liquefaction and lateral spreading have been documented at the rivers, as well as resulting bridge damages and bank failure (NZ-GEER 2010; NZ-GEER 2011). In the context of flood risk, such changes in general river morphology are of high interest (Neuhold et al., 2009).

The review of a time series of Google Earth images and aerial photos in Figure 3-9 gives a first insight into changes in river morphology. Regarding a short section of the Avon River in the vicinity of the Anzac Bridge, which suffered noticeable damages during the earthquake (NZ-GEER 2011), the river banks can be described as well-defined and distinguishable in the Google Earth image from March 2009. In the aerial photo (Canterbury Geotechnical Database, 2012) from September 2010 the northern banks of this section, in particular, are washed out and the river appeared to be widened. In 2011, this process appears to have increased slightly, while a shoal at the southern side of the river seems to be present.



Figure 3-9 Time series of Google Earth images and aerial photos (Canterbury Geotechnical Database 2012) from March 2009 to September 2013 showing a short section of the Avon River in the vicinity of the Anzac Bridge (Anzac Drive: -43.500924°, 172.701084°).

More insights are given in a study by Tonkin & Taylor relating changes in river morphology to horizontal ground motion. In Figure 3-10, two Avon River cross-section topographies are shown. Both cross-sections represented sites at which major horizontal movement (>1.2 m) occurred. Cross-section 6 located between Avondale Bridge and Anzac Bridge is a rather narrow (ca. 22 m) and deep (~2.8 m in 2008) part of the Avon River, and was subject to significant earthquake-

induced infilling of the channel. This is expressed in a shallower water depth of ~1.8 m in 2011, and a decrease in slope of the submerged part of the banks, especially at the northern bank. Such decreases in cross-sectional area of the river potentially lead to higher water levels, higher flow speeds and a higher risk for overtopping of the banks during floods. Higher flow speeds can positively contribute to a natural deepening of the channel, but also to increased erosion and destabilization of the banks and scour, for example, at Anzac Bridge. Section 5 is crossing approximately between Horseshoe Lake Walk and Prestwick St. Here, the Avon is significantly wider (~60 m) with a water depth of ~1.8 m in 2008. Despite major horizontal movement, infill of the channel can only be observed at the eastern 25 m of the river, decreasing the water depth slightly to 1.2-1.6 m. As expected, the horizontal movement had less impact on this wider section of the river, likely leading to no relevant changes in flow conditions.

Four more cross-sections were examined in Figure 3-11 along the Avon River going upstream from the previous river section. Cross-section 4 is located between Ngarimu St and Gloucester St Bridge. In 2008, this cross-section was characterized by a width of ~24 m, a maximum water depth of ~ 1 m and shoal (water depth ~ 0.4 m) approximately in the center of the channel. This area was subject to significant horizontal movement southwards. This led to a shift of the northern bank narrowing the river to a width of ~20 m. Furthermore, the river depth decreased to a depth approximately equal to the depth of the previous shoal (~ 0.4 m). The deeper channel south of the shoal was entirely filled in, while the southern side of the channel steepened. Crosssection 3 is located approximately where Bowie Place turns off Avonside Drive, and was affected by significant horizontal movement pushing from both sides into the river. However, regarding river infill, the stronger southwestward movement clearly dominated and shifted the eastern bank about 3 m into the river, narrowing the river width to ~ 16 m. At the same time, the water depth was decreased from ~ 1 m to ~ 0.4 m. Cross-section 2 (approx. at the eastern end of Robson Abe) and cross-section 1 (just downstream of Banks Ave) were both mainly impacted by horizontal movement from the south/west. In both cases, the northern/north-eastern bank remained steady, while the southern/south-western bank was shifted by ~ 5 m into the river and the water depth at the deeper part of the channel decreased by ~ 0.5 m to 0 to 0.3 m. This confirmed the previous observation and expectation that the narrower river sections suffered more from horizontal movement, while the sediment contribution at wider section appeared rather insignificant.

After 2011, large sections of the rivers have been subject to dredging activities to restore the original river morphology and decrease flood risks associated with the smaller river cross-sectional areas (discussions with representatives of the Christchurch City Council). Dredging activities and post-dredging investigations of river morphology were overseen by the Christchurch City Council and confirmed the restoration of approximately pre-earthquake conditions at a large number of critical river sections. Specific data has not been published yet. According to these results, the increased flood risk at these rivers has likely been adequately
mitigated by restoring the river morphology to pre-earthquake conditions. New and improved dredging equipment will also ensure future stability of the river morphology.



Figure 3-10 Map of earthquake induced horizontal ground movement along the Avon River section covering the area hugging Avonside Drive and a part of the Avon River between Avondale Bridge and Anzac Bridge (courtesy of Tonkin and Taylor), including the topographies of two river cross-sections in 2008 and September 2011.



Figure 3-11 Map of earthquake induced horizontal ground movement along the Avon River section covering the area from Avonside Drive and to Stanmore Road Bridge (courtesy of Tonkin and Taylor), including the topographies of four river cross-sections in 2008 and September 2011.

Improvements and specifying LiDAR

Aerial LiDAR surveys proved extremely beneficial for post-earthquake geotechnical and hydrological evaluations. The CES provided a unique opportunity to use LiDAR in a new capacity. As a result, this section describes some areas where LiDAR was successfully used to great benefit and lessons learned for improving LiDAR use in the future.

While aerial photography is a valuable resource, there is little doubt that the detailed topographic information provided by the aerial LiDAR has both accurately quantified and provided valuable insights into the ground surface movements during the CES. The engineering and insurance communities have already benefited immensely from understanding and quantifying the ground surface and how it has changed, and the scientific community will no doubt continue to mine this rich data source.

A significant portion of the value derived from the Christchurch LiDAR data relied on LiDAR surveys for hydrological modeling that were commissioned by local government agencies before the 4 September 2010 Darfield Earthquake. While Christchurch was subjected to a sequence of

earthquakes, and would have still benefited had the LiDAR data acquired one day after that first earthquake been the only survey available, these hydrological surveys provided important baseline information to quantify movements during that first earthquake.

A serendipitous benefit of the hydrological LiDAR surveys was that they covered a significantly greater area than could be justified for the 5 September 2010 LiDAR, which was primarily for emergency management purposes. Subsequent surveys were commissioned with greater extents, particularly once the value of LiDAR was more widely appreciated within the insurance and engineering communities and once this benefit was realized by central government agencies able to fund such data gathering efforts. While their principal uses to date have been quantifying land damage (e.g. subsidence, lateral spreading and increased flood vulnerability), they are an invaluable resource for identifying and devising remediation solutions for both widespread and localized areas of change.

The surveys later in the earthquake sequence aimed to provide better topographical accuracy by acquiring the LiDAR once liquefaction ejecta was judged to be mostly removed from the ground surface (and either piled in streets or trucked away). This contrasts with aerial photography that was more usefully flown as soon as practicable after the earthquake in order to record the extents of liquefaction ejecta.

While baseline LiDAR surveys are invaluable for identifying elevation changes after significant earthquake events, the Christchurch experience indicates that they need to be regularly updated in any area being monitored. While an obvious purpose of this is to record changes in land use, capturing the pre- and post-event point clouds using similar instruments maximizes the value of the post-event data because the earlier data will have similar precision, accuracy and point density. Short time intervals between surveys also allows for more certainty in isolating earthquake induced changes from background geomorphic dynamics. The Christchurch coast dunes, for example, had grown significantly via aeolian processes between the pre-quake 2003 LiDAR survey and the first post-quake survey, making the determination of exact earthquake-induced deformation of the shore-proximal coastal plain impossible.

A third driver for regular pre-earthquake updates is data retention. While the 2003 LiDAR point cloud was stored in a format that was easily revised 8 years later to use an improved geoid offset model published in 2009, only the thinned ground returns had been retained. This could be because only that subset of the data, which was still a reasonable portion of the capacity of a hard disk in 2003, was regarded as valuable enough to maintain in an accessible format. Periodic updates could maintain an active interest in using the data and thereby ensure it is well curated from machine to machine and person to person.

Publication of one form of LiDAR on the Canterbury Geotechnical Database (CGD), in a format that is almost universally accessible without specialized Geographical Information Systems knowledge or (expensive) software, has also helped the engineering community understand what

it is and how it can be used. Publishing LiDAR in an equally accessible format in areas that could be subject to extreme ground level altering events, including earthquakes, cliff collapses, and landslides, would not only go some way toward encouraging regular LiDAR updates, but would ensure that the local engineering community understand its value and frequently use it well before they need to use it for emergency response purposes.

Most mapping in the CGD and large scale analysis has relied on Digital Elevation Models (DEM) defined by averaging the ground surface elevations within 5 m square cells rather than the full point clouds. This cell size appears to be the best compromise between increasing the number of returns in each cell to improve the accuracy and minimize the cell size to provide an adequate representation of the variation in surface elevations.

The number of cell returns was particularly important for the DEM constructed from the sparser 2003 (hydrological) LiDAR, but also provided DEMs that were reasonably easily stored and processed. Ideally, water penetrating LiDAR instruments should be used in areas with significant waterway, coastal and/or estuarine features. In Christchurch the earlier LiDAR surveys were non-water penetrating, limiting the ability to detect elevation changes across the Avon-Heathcote Estuary Ihuati. Boat and ground based surveys were used to determine that two thirds of this feature had been uplifted but the coverage of these surveys, which were completed using grids and transects, was not as thorough as could have been provided using water penetrating LiDAR.

A reasonable amount of effort was expended to verify the accuracy of the LiDAR (CERA, 2014). This showed that the accuracy of each entire LiDAR point cloud is close to the accuracy of New Zealand's geoid offset model, representing the difference between GPS-based and precise leveling surveys. However there was better precision available within localized subsets of the point cloud (e.g. hard surfaces such as streets). The verification benefited from a good source of surveyed reference benchmarks. Benchmarks on the ground surface were more easily compared with the LiDAR point cloud than those buried below (often not well defined distances below the ground surface).

Most Christchurch properties appeared to have an adequate portion of their total area visible to the LiDAR scanner (i.e. uncovered by structures or obscured by vegetation) to provide adequate representations of the ground surface elevations. Similarly, while seasonal vegetation differences didn't appear to have much observable effect on the DEMs for Christchurch, this could be an issue in more densely vegetated or built up urban areas.

Finally, horizontal ground movements were estimated by correlating elevations within pairs of DEMs. This required a significant amount of work to remove systematic noise that produced chessboard-like patterns in larger areas than those illustrated in the Figure 3.1 elevation differences. A significant recommendation resulting from this analysis was that LiDAR flight paths need to be reasonably similar to provide better estimates of horizontal movements.

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4 PRE & POST EARTHQUAKE FLOOD MODELLING

Extensive flood modelling has been completed for the City of Christchurch. This section outlines the modelling before and after the 2010-2011 Earthquake sequence. Land surface changes, discussed in Chapter 3, have contributed to changes in the areal extent of flooding. The modelling, groundwater and estuary are reviewed in this chapter with respect to changes that occurred as a result of the 2010-2011 Canterbury earthquake sequence.

4.1 Pre-earthquake Christchurch City Council Flood Management Area maps

The GEER team interviewed Mr. Graham Harrington, Senior Surface Water Planner for the Christchurch City Council (CCC), for information relating to the development of both the pre and post-earthquake Flood Management Area (FMA) maps. Prior to the Canterbury earthquake sequence, the CCC had identified areas that were prone to flooding from events such as major high tides or rainfall. These areas were also recognised as vulnerable to sea level rise (SLR) and the effects of climate change. The CCC modelled this risk and produced a FMA map (Figure 4-1) to inform the District Plan of minimum building floor levels.

Operative Variation 48 was established to assist the CCC to meet its statutory obligations with respect to floodplain management under the Resource Management Act 1991 (RMA) and is included in the District Plan (CCC, 2011). Operative Variation 48 was established because areas of Christchurch that were flood prone had floor levels set by the Building Act 2004, which only considered a 1 in 50 year precipitation event. Additionally, it was not thought at the time, in 2003, that the expected 0.5 m of SLR by the end of the century could be legally accounted for within the Building Act. This policy has changed and the allowance of 0.5 m SLR is routinely used in setting residential design floor levels under the Building Act.

Figure 4-1 shows the pre-earthquake FMA as modelled. This map was produced using a development scenario incorporating a 200-year return-period rainfall event, plus a 16% buffer allowing for a 2 degree temperature rise and 0.5 m of SLR by the end of the century. The flood level was created using DHI 1D models, with land elevations derived from the 2003 LiDAR data as a key input. The model is limited in extent to the areas around major rivers and some other flood plain areas around the city based on historical flooding experience. The model was not all inclusive, and did not include groundwater. Rather it was developed during the period 2003 to 2005 to allow the city to adapt to, and plan for, climate change and sea level rise. The FMA extends beyond the modelled flood level boundary to provide for a 400 mm freeboard on potentially affected homes. The 400 mm (FMA) of freeboard is made up of 250 mm added to the predicted surface flooding level, with an additional 150 mm which accounts for slab on grade foundations. This 400 mm level above the modelled extent was then projected sideways, encompassing more homes to create the final FMA.



Figure 4-1 Pre-earthquake FMA developed by the CCC (Christchurch City Council, 2010).

4.2 Post-earthquake flood modelling: the Christchurch City Council FMA

The CCC has developed a post-earthquake updated, proposed FMA (Figure 4-2 and Figure 4.3), which has been released for comment under the District Plan review process. The updated FMA was required by the regional council, Environment Canterbury (ECAN), whose policy change recommends that the CCC provide 200-year return-period flood protection.

The proposed FMA is also based on the methodology set out in section 4.1 with some changes. The flood modelling extent has been expanded over the city (as seen in Figure 4-3 and 4.3) with some modelling data yet to be confirmed. A post-earthquake LiDAR dataset was used to generate the new landform for the model to account for ground deformations such as subsidence and uplift within the city, and again groundwater was not used as an input. The extent of the proposed FMA is slightly larger than the modelled 200-year return period rainfall flooding extent, due to the additional 400 mm freeboard outlined in section 4.1 above. An important note is that the new proposed FMA has significantly larger coverage in eastern Christchurch due partly to landform model changes from the post-earthquake LiDAR data set and more so from the policy change to use the 200-year return period event across the city rather than the earlier policy of only including 50-year return period events and the areas near the sea and alongside the major rivers.

A recently released CCC commissioned report 'The Effects of Sea Level Rise on Christchurch City' recommended that CCC adopt a 1 m SLR strategy for the District Plan for timeframes up until the end of this century (Tonkin & Taylor, 2013). Graham Harrington, Senior Surface Water Planner from CCC has recommended that Christchurch adopt the 1 m SLR adaptation strategy in line with the report recommendations for the District Plan. The CCC District Plan is currently under review.

4.3 Tonkin & Taylor 'Increased Flooding Vulnerability' modelling

The team met with Tonkin & Taylor (T&T), a engineering and environmental consultant for the Earthquake Commission (EQC) currently working on the EQC category 9 land damage assessment program. T&T is leading the Increased Flooding Vulnerability (IFV) project. The IFV project was set up to inform EQC of the increased flood risk exposure in Christchurch and to define the extent for EQC land insurance settlement purposes. This process is driven by the Earthquake Commission Act 1993. The project is currently undergoing its final peer review process by international and national experts.

Modelling was carried out using both the DHI MIKE software suite (<u>http://mikebydhi.com/</u>) and TUFLOW packages (<u>http://www.tuflow.com/flike.aspx</u>). Groundwater changes, storm surges and climate-change induced sea level rises were not considered in this exercise. The model gave a 'snapshot in time' and differed from previous CCC modelling in that T&T developed an overland flow model to account for observed flooding outside of the major waterways. A major issue with the modelling was the accuracy of the pre-earthquake (2003) LiDAR data, which was never intended to form the basis of a flood modelling digital elevation model. The accuracy of the LiDAR data, specifically the sparse data points, has been a limiting factor of the project modelling to date.

The flooding observations carried out by both CCC and T&T are shown in Figure 4-4 The map is compiled from the March flood event observations that had been mapped at the time of this report. Note that no reconciliation of the frequency attributed to the flood event had been carried out to date. Hind-cast simulation modelling of the March 5th event was carried out using the TUFLOW software package and is shown in Figure 4-4 (Tonkin & Taylor, 2014).



Figure 4-2 Existing and proposed Flood Management Area (FMA) with a 0.5m SLR (Christchurch City Council, 2014).



Figure 4-3 Existing and proposed Flood Management Area (FMA) with a 0.5m SLR (Christchurch City Council, 2010, 2014).



Figure 4-4 Observed flooding in Christchurch March 2014 versus hind-cast model predictions (Tonkin & Taylor, 2014).

4.4. Pre & Post- earthquake 100 year return period flood modelled maps

CCC has modelled the change in 100-year return period flood events for Christchurch in a post vs pre-earthquake scenario. Graham Harrington kindly provided the modelled pre- and post-earthquake 100-year return event maps for the Avon and Heathcote Rivers, noting that stopbanks were not included in the modelling. The Avon River and Southshore area changes in 100-year rainfall event flooding are shown in Figure 4-5 with the post-earthquake increase in flood extents indicated by the lighter blue color. Modelling indicates that under pre-earthquake conditions 1,820 properties could have be affected while in the post-earthquake scenario an estimated 3,720 properties could now be affected by flooding, showing the earthquake effects have more than doubled the number of properties at risk of flooding in this one area of the city.

The above flood predictions cover the lower Avon catchment. As explained in Chapter 2 of this report, this river represents one of the two main urban rivers flowing through Christchurch and draining into the Avon-Heathcote Estuary Ihutai. The other main urban river in Christchurch is the Heathcote, which lies to the south and west of the estuary. The Heathcote River changes in predicted 100-year flood extents are shown in Figure 4-6.



Figure 4-5 Avon River and Southshore change in 100-year predicted flood extents, with no stop banks. Dark blue indicates pre-earthquake flooding, light blue indicates the increase in flood extents post- earthquake (Harrington, 2014).



Figure 4-6 Heathcote River pre and post-earthquake 100 year predicted flood extents, (Harrington, 2014).

4.5 Groundwater

As explained in Chapter 2 of this report, the hydrogeology of the Canterbury plains are largely Quaternary deposits of gravel, sands and silts that formed as outwash fans from the braided channel rivers that formed as the Southern Alps were uplifted, with a layer of sandy coastal progradation deposits forming the Holocene subsurface of the city. In the Quaternary layers below Christchurch City, the alluvial deposits, mainly from the Waimakariri River, occur in alternating layers with a series of marine deposits. The marine deposits can be found at depths up to 15 km under Christchurch City from the current coastline. The alternating layers of gravel and marine deposits occurred because the gravel was deposited during periods of lower sea levels and the marine deposits have lower permeabilites and create a system of confined aquifers along the coast (Weeber, 2008). The system is recharged by infiltration from precipitation and irrigation and from the surface water flows from the Waimakariri River. Due to seasonal variation in the recharge sources, variability in the groundwater levels can also be observed in historical data.

Along the coast, the system discharges to the ocean. This discharge could reverse and become saltwater intrusion if the groundwater levels lower compared to the sea level or the sea level rises compared to the groundwater levels. To the west of Christchurch city and along the Port Hills, in an area of alluvial aquifers west of the marine deposits, allow groundwater to be discharged through a series of springs. These springs feed the local rivers including the Styx, the Avon, and the Heathcote (Weeber, 2008). Following the Darfield 10 September 2010 Earthquake, a series of new springs emerged to the south and east of the city where few had emerged prior to the earthquakes (White, et al. , 2007; van Ballooey et al., 2013)



Figure 4-7 Environment Canterbury "Christchurch Groundwater Protection" (Weeber, 2008).

In addition to natural discharge, the groundwater system in the Canterbury plain is pumped for numerous uses. Up to 80% of municipal and 50% of agricultural demands in the region are satisfied through groundwater (Brown & Weeber, 1992). The groundwater is of very high quality and does not require treatment for domestic consumption. Because of its high quality, the government has set up an extensive and thorough monitoring program. Following the Canterbury Earthquake Sequence this monitoring programme was significantly expanded.

The groundwater table below Christchurch City is typically less than 10 m deep throughout the area (van Balleooy et al., 2013). Due to the shallow water table, groundwater plays an important role in the liquefaction potential in the city, as well as the potential to increase local flooding. The CCC, ECAN and EQC have data for 806 shallow monitoring wells throughout the city. These shallow wells are less than 10 m deep (van Balleooy et al, 2013). The groundwater table

ranges in depth from less than 1 m to 5 m under the city, and follows the general topography of the land surface.

The local flooding from the rainfall event of on the 5th March 2014 had little contribution from groundwater. Given the time of year and indications from the groundwater records, it is estimated that groundwater levels were near the 85th percentile level under the city (Tonkin & Taylor, 2014)

4.6 Changes in estuary inlet and bed morphology, plus possible ecosystem impacts

Estuaries and their inlets represent some of the most morphologically and ecologically sensitive systems of the coastal zone (Healy et al., 1996). Figure 4-8 illustrates the ocean-side of the Avon-Heathcote Estuary Ihutai inlet. Hydrodynamics, geomorphology and sedimentology interact in these environments in a highly complex manner, potentially leading to rapid and significant system-wide changes when one element of an estuary is altered (Pritchard, 1967).

The Avon Heathcote Estuary Ihutai, Christchurch's main coastal waterbody, underwent significant changes in ground surface elevation during the 2010-2011 earthquake sequence (Figure 4-9). These ground changes, including mainly uplift, suggest possible impacts for the entire system including physical and ecological characteristics.





Figure 4-8 The inlet from the south-side beach perspective (a), and from one of the upper roads on the Sumner side (b) taken on 19 March 2014.



Figure 4-9 Bathymetric changes in the Avon Heathcote Estuary calculated from digital elevation models derived from a composite of LiDAR and echosounder survey data. The change analysis shows that the main body of the estuary has experienced uplift with some subsidence in the northern end around the mouth of the Avon River. Uplift patchiness in the southern part of the estuary represents morphological change between surveys rather than earthquake effects. A full description of the digital elevation models used for this analysis is contained in Measures (2013).



Figure 4-10 Time series of Google Earth images of the inlet (43° 33' 41.45"S, 172° 45' 14.44"E) and the estuary from 29 January 2003 to 25 April 2013. For direct comparison of the inlet and estuary morphology, it has to be considered that the images have not been referenced to the respective tidal phases yet.

To demonstrate the rapid changes from the earthquake sequence, a time series of Google Earth images from 2003 to 2013 is shown in Figure 4-10. The images indicate no significant changes of the inlet from 2003 to 2009. However, in the 2010, a distinct channel can be seen interrupting the line of breaking waves, likely corresponding to a sandbar-like feature as can often be observed at deltas and inlets. This behaviour can continuously be found in the following images. A generally limited wave action must also be considered an influencing factor. A major change in inlet morphology can then be seen in the image from 2013. The channel at the ocean side bends northward leading to a pointed flat at the southern side of the inlet. Entering the estuary, the channel bends southward, intensifying the meandering loop that seemed to have had less significance in the past, and creating a larger flat at the inner side of the end of the spit (Figure 4-10). It should be noted that the Google Earth images are not referenced to a particular tidal phase and state of wave action, introducing a degree of variation when comparing the images.

To examine changes in hydraulic behaviour, NIWA has carried out a detailed study of the morphological changes of the estuary and inlet including a numerical hydraulic modelling over pre- and post-earthquake topography. The observed and ongoing changes in geomorphology, regarding the inlet and channel dynamics as well as the uplift and subsidence in the estuary, are expected to interact with tidal and possibly sediment characteristics. The average tidal prism of the estuary has reduced from 9.5 million m³ prior to the earthquakes to 8.1 million m³ after the earthquakes. This leads to changes in the state of inundation across the estuary over a tidal cycle, as indicated in Figure 4-11, as well as changes to saltwater wedge penetration up the Avon and Heathcote River channels. Such changes can represent a major change for the eco-system, especially related to overall changes in the salinity level (Crain et al. 2004). In conjunction with flood events introducing high amounts of freshwater into the system, areas might undergo more rapid as well as long-term changes in inundation and salinity (Pennings et al. 2004). The reduced tidal prism volume (14.6% reduction) has also resulted in a substantial narrowing of the inlet as shown in Figure 4-12. It is expected that the reduced tidal prism will lead to smaller ebb and flood-tidal deltas, with the surplus sand distributed onto the adjacent beaches.



Figure 4-11: Proportion of time estuary bed is submerged pre and post-earthquake. Clear changes are visible in the southern and eastern parts of the estuary which are having significant effects on habitat and morphology. Figure reproduced from Measures (2013).



Figure 4-12 Changes in mouth cross-section pre-earthquake (1998), immediately post-earthquake (March/April 2011) and following morphological adjustment (January 2013). Cross-section extracted from echo-sounder surveys of the neck of the estuary. Figure reproduced from Measures (2014).

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5. EFFECTS OF EARTHQUAKE-INDUCED GEOTECHNICAL IMPACTS ON FLOODING

At the behest of CCC, T&T have performed both pre- and post-earthquake sequence overland flow and river flood modelling (Tonkin and Taylor, 2013). In this section, the river flood modelling outputs are compared with the seismic-induced geotechnical mechanisms that have played an important role in increasing the flood susceptibility in Christchurch, including vertical tectonic movements, liquefaction induced settlement, lateral spreading, and river channel capacity changes. Many factors other than these mechanisms, which influence overland and river channel flow, are recognized to have contributed to the observed flooding during the 5th March 2014 event. These include earthquake-induced damage to pre-existing flood protection and stormwater systems, and to other key water-conveying infrastructure, along with further impacts such as those from construction-induced obstructions and ecological system impacts. An overview on these aspects is provided in the following chapters.

Tectonic Uplift and Settlement (Heathcote River)

LiDAR mapping from CERA Project Orbit indicates that there has been both land uplift and settlement over the lower Heathcote River catchment.

The Heathcote River lower section is tidally influenced and, as shown in Figure 5-1a, has risen by up to 400 mm, while the upstream portion of the river has settled by 100-300 mm. The mechanisms leading to this deformation pattern were described in Chapter 3. These elevation changes have resulted in a gentler hydraulic gradient, reducing the river's hydraulic capacity and leading to increased bed levels (CCC Task Force, 2014). As example of the settlement along the Heathcote River, stop-banks constructed in 1986 in the vicinity of Radley to Garlands Roads have settled by up to 0.5 m (River Level 10.9 m to 10.4 m). Since the 2010-2011 earthquake sequence the ecology of the Heathcote River has begun to adjust to this change in the river-scape, with the re-establishment of invertebrates in the lower section.

Overland flow modelling was carried out by T & T, using both the DHI MIKE software suite and TUFLOW packages (Chapter 4), and making reference to pre- and post-earthquake LiDAR data. Figures 5-1b and 5-1c present maps showing the qualitative comparison for pre- and post-earthquake conditions, respectively, in the Heathcote River lower section, where the tectonic uplift was observed. These figures highlight the reduction of expected overland flow area and a decrease in the expected flood depth: that is, maximum expected flood depth in the area is in the range of 0.7-1 m (Figure 5-1b) for the pre-earthquake conditions and in the range of 0.5-0.7 m (Figure 5-1c) for post-earthquake conditions. However, as previously noted the model does not include groundwater changes, storm surges and climate induced accelerated sea level change. Also, the pre-earthquake LiDAR data (2003) is considered of limited accuracy. Thus the uncertainty in results is not well constrained, but the trend is consistent with observed ground movement and expected changes in flow patterns.



Figure 5-1 Heathcote River area: (a) impacts of tectonic uplift (Tonkin & Taylor, 2013); (b) pre-100 year annual return interval (ARI) event flood depth; and (c) post 2010-2011 earthquake sequence ARI event flood depth excluding stop-banks and climate change (Tonkin & Taylor 2013).

Liquefaction induced settlement and effects on flooding of the Heathcote River

Liquefaction induced settlement was documented in Christchurch and the surrounding communities after the four main events included in the 2010-2011 Canterbury earthquake sequence. Tonkin & Taylor (2013) documented elevation changes in the period from pre-2010 to December 2011.

In the Heathcote catchment area Figure 5-2a shows both settlements and uplift of ≤ 0.3 m were experienced. Canterbury Geotechnical Database (CGD) data show that vertical and horizontal ground movements occurred in the upper Heathcote River area (i.e. the area from Halswell Road to Cashmere View Street on both sides of the Heathcote River), with the land generally settling between -0.1m to -0.3 m after the earthquake events.

Figure 5-2b shows the resulting cumulative changes in overland flow flood depths estimated by T & T, taking into account both pre- and post-earthquake land elevations, which included both liquefaction-induced settlement and tectonic uplift. Figure 5-2b shows liquefaction induced settlement in the middle reaches of the Heathcote River increased the flood depth by up to 0.5 m.



Figure 5-2 Heathcote River: (a) cumulative elevation change along the river pre-2010 to post June/December 2011 (Tonkin & Taylor Ltd, 2013, Figure A10); (b) overland flow increased flood depths post-December 2011 compared to pre-September 2010 (Tonkin & Taylor, 2013).

Liquefaction Induced Settlement and Effect on Flooding (Avon River)

Figure 5-3a shows the estimated Avon River catchment area cumulative changes in overland flow flood depth, as assessed by T & T, taking into account both pre- and post-earthquake land elevations. These results indicate an increased flood depth up to 1 m in this area, resulting from the cumulative settlement shown in Figure 5-3b from the 2010-2011 earthquake sequence exceeding 1 m within the same area.



Figure 5-3 Avon River: (a) overland flow increased flood depth for the Avon River pre-September 2010 to post-December 2011; (b) cumulative elevation changes due to liquefaction; (c) increased overland flow flood depth from the overland flow model for the 100 year ARI excluding stop-banks and climate change for pre September 2010; and (d) post 2010-2011 earthquake sequence (Tonkin & Taylor, 2013).

Modelling of the overland flow was carried out by T & T, using both the DHI MIKE software suite and TUFLOW packages (Section 4), and making reference to pre- and post-earthquake LiDAR data. Figures 5-3c and 5.3d present maps showing the qualitative comparison of the pre- and post-earthquake conditions, respectively in the Avon River lower section. These results highlight an increase in the expected flood depth: that is, maximum expected flood depth in the area is in the range of 0.5-0.7 m (Figure 5-3c) for the pre-earthquake conditions, while expected to exceed 1 m in post-earthquake-conditions (Figure 5-3d).

Liquefaction induced settlement and effect on flooding of the Dudley Creek catchment, including the Flockton area

Dudley Creek and its tributaries are demonstrably under capacity in rainfall events. The Flockton area (around Flockton Street), having the topography of a basin, is one of the most flooding-prone areas within the Dudley Creek catchment (CCC Task Force, 2014). Even before the 2010-2011 earthquake sequence the Flockton area was prone to flooding, and often suffered from significant ponding. Since the earthquake sequence the area was flooded in August 2012, June 2013, and March 2014 showing how the frequency and magnitude of flooding seems to have increased (Chapter 2).

Jacobs Sinclair Knight Merz (JSKM), who conducted the Dudley Creek project under the Land Drainage Recovery Programme, have extensively studied the Dudley Creek catchment including the Flockton area. An increase up to 0.5 m in flood depth can currently be observed in the Flockton Basin when comparing the peak flooding depth expected for a 10-year return-period rainfall event pre-September 2010, resulting from the JSKM study and shown in Figure 5-4a, with the peak flooding depth expected for the same rainfall event in post-earthquake sequence condition shown in Figure 5-4b. This increased flooding depth is a result of subsidence across a large proportion of the Dudley Creek catchment. Subsidence of between 0.2 and 0.5 m is shown in Figure 5-4c, resulting from the 2010-2011 earthquake sequence. Bed heave has also occurred extensively along Dudley Creek and its tributaries, resulting in a subsequent loss in hydraulic capacity.



Figure 5-4 Dudley Creek catchment, including the Flockton area: (a) height of flood water for a 10-year return-period rainfall event pre-September 2010 (CCC, 2014); (b) increased height of flooding for same rainfall event post-earthquake sequence (CCC, 2014); (c) cumulative liquefaction induced settlement in the area as a result of the 2010-2011 earthquake sequence (Tonkin & Taylor, 2013).

Lateral spreading and river channel capacity reduction effects on flooding of the Avon River

Figures 5-5a and 5-6a illustrate the moderate to severe lateral spreading that has occurred along the length of the Avon River, where major horizontal movements in excess of 1.2 m were observed as a result of th4e 2010-2011 earthquake sequence.

As previously described in Chapter 3 and shown in cross-section 6 in Figure 5-5a, the channel area between Avondale Bridge and Anzac Bridge was subject to significant infilling following the 2010-2011 earthquake events, resulting in a shallower water depth of ~1.8 m in 2011. The Avon River banks suffered significant slumping from liquefaction and lateral spreading. Figure

5-5a cross-section 6 clearly shows a shallower slope on submerged banks, especially on the northern bank.

Qualitative comparison of the T&T overland flow maps for pre (Figure 5-5b) and post (Figure 5-5c) earthquake conditions along the Avon River in the area from Avondale Bridge to Anzac Bridge highlights an extended overland flow and an increase in the expected flood depth of up to 0.7 m (Figure 5-5c).



(a)

(c)

Figure 5-5 Avon River from Avondale Bridge to Anzac Bridge: (a) post-earthquake sequence cross sections; (b) pre-earthquake sequence river flood depth modelling for the 100 year ARI, excluding stop-banks and climate change; and (c) post-earthquake sequence river flood depth modelling for the 100 year ARI, excluding stop-banks and climate change (Tonkin & Taylor, 2013).



Figure 5.6 Avon River from Avonside Drive to Stanmore Road Bridge: (a) post earthquake sequence cross sections; (b) pre-earthquake sequence river flood depth modelling for the 100 year ARI, excluding stop-banks and climate change; and (c) post-earthquake sequence river flood depth modelling for the 100 year ARI, excluding stop-banks and climate change (Tonkin & Taylor, 2013).

Figure 5.6a presents the horizontal movements (up to 1.2m) observed along the Avon River section in the area from Avonside Drive and to Stanmore Road Bridge. In Section 4 of Figure 5.6a a shift of the northern bank narrowing the river to a width of around 20 m can be observed, along with a decrease of the river depth of around ~0.4 m. At cross-section 3 the river width was narrowed to around 16 m and the water depth was decreased from approximately 1 m to 0.4 m. For both cross-sections 2 and 1 the northern/north-eastern bank remained steady, while the

southern/south-western bank shifted laterally by around 5 m into the river and the water depth at the deeper part of the channel decreased by around 0.5m to between 0 and 0.3 m. Further details and comments on the earthquake-induced impacts and changes to river morphology can be found in Chapter 3 of this report.

The qualitative comparison of the T&T overland flow maps for pre (Figure 5-6b) and post (Figure 5-6c) earthquake conditions for the Avon River highlights, in the area from Avonside Dive to Stanmore Road Bridge, an extended overland flow and an increase in the expected flood depth that is expected to exceed 1 m (Figure 5-6c). It is worth noting that the overland flow model, while accounting for the earthquake-induced changes in the river morphology does not account for stop-banks and climate change. The performance of the Avon River stop-banks after the 2010-2011earthquake sequence is described in Chapter 6 of this report.

Figure 5-7 shows the pre- post-earthquake estimated Avon River flood depths (Tonkin and Taylor, 2014). A comparison of these figures identifies increased river flooding depths of over 1 m along portions of the Avon River and in the Avon-Heathcote Estuary Ihutai.



Figure 5-7 Increased river flood depths for the Avon River, excluding stop-banks and climate change for the 100 year ARI for (a) pre September 2010 and (b) post 2010-2011 earthquake sequence (Tonkin & Taylor, 2013)

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6. GEOTECHNICAL EFFECTS ON CRITICAL STRUCTURES DURING THE MARCH 5TH FLOOD EVENT

Flood induced geotechnical failures were investigated by the GEER team during their deployment for the March 5th flood event. Bridge scour was investigated on bridges along the Avon and Heathcote Rivers. The GEER team visited the port in Lyttelton to explore damage that may have been induced by the flood event. Updates to GEER's reconnaissance conducted after the February 2011 Christchurch earthquake are also presented that could not be previously released due to economic sensitivities for Lyttelton Port Christchurch (LPC). Lastly, the potential failure of a newly constructed earth retaining wall in the Port Hills is explored.

Bridge scour

Scour represents one of the major failure mechanisms of bridges (Melville and Coleman, 2000). In particular, the increase in water flow velocities during heavy rain and flood events can lead to increased sediment erosion in the vicinity of bridge piles, and by doing so, potentially lead to failure of the bridge. Due to the complex and interdisciplinary nature of the processes (Sumer and Fredsoe 2002), the prediction of scour and potential bridge pile failure is still a subject of research. In Christchurch the impact of the previous earthquake related damage to the bridges and possible changes in river morphology represent another variable that is still in the process of being considered and investigated.

The GEER team conducted a rough survey of possible scour at four Avon River bridges identified in Figure 6-1 and two Heathcote River bridges identified in Figure 6-2. Figure 6-3 shows how the water depth was sounded along the bridges, using a diving weight and a marked rope. Indications for scour were mainly found at Pages Street Bridge and Wainoni Road (Bower) Bridge (both crossing the Avon River; Figure 6-1). However, large uncertainties have to be considered regarding the simple and coarse sounding technique. Detailed investigations including more measurements around the foundations would allow more definitive conclusions to be made. In the following sections, a background of the bridges is given and the results of the soundings presented.



Figure 6-1 Bridges surveyed regarding possible scour along the Avon River.



Figure 6-2 Bridges surveyed regarding possible scour along the Heathcote River.





(a)

(b)

Figure 6-3 (a) Depth soundings at Anzac Drive Bridge and (b) depth reading using a marked rope.

A) Avon River Bridges

Bridge Street Bridge

The South Brighton Bridge, or Bridge Street Bridge, crosses the Avon River in an east-west orientation, connecting the suburbs of South New Brighton and Bromley (Figure 6-1). It is the final crossing on the Avon before it enters the Avon-Heathcote Estuary, and provides the primary link for the suburbs of South New Brighton and Southshore.

Original structure

The original bridge was constructed in 1981 and had a total length of 65 m over three spans of in-situ cast concrete supported by precast post-tensioned concrete I-beams (21.5 m-22 m-21.5 m) and a total width of 15.2 m. Details of the original plan and elevation are provided in Figure 6-4 and Figure 6-5. To construct the bridge, two approach embankments approximately 4 m in height were extended out into a wetland area, with the bridge structure spanning the river channel.

The spans are supported by octagonal precast concrete piers with hammerhead pier caps and seat-type concrete abutments. Elastomeric bearings have been used to isolate the super-structure in both the longitudinal and transverse directions. Both piers and abutments are supported by raked pre-tensioned reinforced concrete octagonal piles (450 mm wide and 18.7 m in length). These are installed at the piers with a rake of 14° from vertical. Each abutment has ten piles, and each pier is supported by a pile cap with twelve piles.


Figure 6-4 General planform design of South Brighton Bridge, with the left of the figure the western edge of the bridge (CCC, 1978).



Figure 6-5 Profile view of South Brighton Bridge (CCC, 1978).

Earthquake Damage

The bridge was affected by the Darfield, Christchurch and 13 June 2011 earthquakes, with some minor additional land damage following the 23 December 2011 earthquake. The bridge sustained moderate to severe damage following the Darfield earthquake, severe damage following the Christchurch earthquake, and this was further damaged following the 13 June 2011 earthquakes.

Both abutments settled and back-rotated as a result of lateral spreading. Following the 13 June 2011 earthquakes, back-rotation of the western abutment was equal to 10°, while the eastern abutment had 9° of back-rotation. The slumping of soil around the abutments due to lateral spreading exposed the tops of the abutment piles. Hinging at the top of the piles was accompanied by horizontal flexural cracks and spalling in the exposed sections of the piles under both abutments. Following the Darfield earthquake only minor cracking of the piers was observed, with a single flexural crack at the water line in the west pier. There was no serious damage to the bridge superstructure, however greater subsidence at the abutments compared to the piers meant that the superstructure developed a hogged profile.

Retrofit of structure

Retrofit of Bridge St Bridge commenced in 2013, involving strengthening of the bridge structure and stabilisation of the river bank and embankment slopes at the abutments with a jet grouted column lattice structure to mitigate liquefaction and lateral spreading effects. Four 1.2 m diameter concrete filled steel tube piles will be installed at each abutment to a depth of approximately 40 m into dense gravels. The superstructure will be jacked level to reduce stresses caused by the hogging, and abutments were rebuilt with geogrid (Keepa et al., 2014). This work is estimated to be completed in mid-late 2014.

Scour

With the original river bed level (Figure 6-5), scour would correspond to the octagonal columns, probably reaching the pile caps and making them a scour protection. With full exposure of the pile caps, scour would be expected to develop in a different shape, in response to the sharp pile cap edges. However, destabilization of the bridge due to scour is very unlikely, because of the support provided by the concrete piles. Surveying was limited due to construction work (Figure 6-6, Figure 6-7, and Figure 6-8). Figure 6-8 shows the soundings generally indicating a deepening towards the east in the channel, and the downstream side was generally deeper by ~30-40 cm. An irregularity was found at a distance of 24-26 m from the western lightpost which served as datum. Due to the limited soundings, it cannot be determined if the shoaling or the deepening represents the irregularity, or if this might be related to a gravel bank deployed around the piers for a remediation of the pier pile caps. A more detailed investigation after the conclusion of the construction work would answer this question.



Figure 6-6 Sounding at South Brighton Bridge with construction work in the background on 19 March 2014.



Figure 6-7 Location of upstream (yellow) and downstream transects superimposed on aerial photo from 24 December 2011 (Canterbury Geotechnical Database 2012).



Figure 6-8 Soundings at the Avon's Bridge Street Bridge. Zero represents the western lightpost of the bridge. Construction work restricted the sounding particularly on the upstream side, and in close vicinity of the piers.

Pages Road Bridge

The Pages Road Bridge, or New Brighton Bridge, crosses the Avon River in an east-west orientation on the eastern edge of the city, connecting Christchurch to the suburb of New Brighton. It was opened for traffic on May 2^{nd} 1931. The bridge acts as a crossing point for a number of utility services crossing the bridge path.

Original structure

Pages Road Bridge is a cast in-situ monolithic reinforced concrete structure which was designed in 1924, and constructed in 1930-31. Details of the plan and elevation are given in Figure 6-9 and Figure 6-10. The bridge has a total length of 22.5 m over three spans (6.7 m-9.2 m-6.7 m) and a total width of 16.8 m.

The deck is supported by two concrete wall piers, with the superstructure fully built into these and the abutments (Figure 6-11). Both piers and abutments are supported by 350 mm wide octagonal reinforced concrete piles, each 7.3 m long. Each pier has 14 vertical piles, while each abutment has eight piles supporting the backwall and two piles supporting each wing-wall.



Figure 6-9 General plan of Pages Road Bridge, with the left of the figure the western edge of the bridge (Toogood, 1929).



Figure 6-10 Elevation view of Pages Road Bridge (Toogood, 1929).



Figure 6-11 Pages Road Bridge on 19 March 2014.

Earthquake Damage

The bridge was mainly affected by the Christchurch earthquake, with some minor additional land damage following the 13 June 2011 earthquake. The bridge sustained moderate damage following the Christchurch earthquake due to liquefaction and lateral spreading, and this was further progressed following the 13 June 2011 earthquakes.

Both abutments developed minor back-rotation and cracking, and there was significant settlement of the approaches as a result of liquefaction and lateral spreading during the Christchurch earthquake. There was a slight increase in the abutment back rotation following the 13 June 2011 earthquakes. Minor cracking at the interface between the eastern pier and the deck beam was identified following the Christchurch earthquake.

Retrofit of structure

The planned retrofit of this bridge, involving improvements to the approach and abutments, had yet to commence at the time of the March 2014 flood event and post-flood GEER reconnaissance.

Scour

Figure 6-12 shows the sounding results at Pages Road Bridge indicating a deepening by ~ 0.4 m and narrowing of the Avon River downstream. The cross-bridge profiles do not indicate scour. However, at the western pier measurements at a distance of ~1 m (cross-profile) and at ~0.1 m were conducted. Downstream of the pier, the water depth equalled ~1.8 m, which was in accord with the general channel profile (Figure 6-12). Close to the pier foundation the water depth was

only ~1.5 m, possibly corresponding to sediment accumulation in the lee of the structure as is typically seen when scour occurs. On the upstream side, a water depth of ~1.6 m was measured at a distance of ~1 m from the piers, while at the pier foundation a water depth of 1.8-1.9 m was measured over four soundings, likely representing a scour hole as typically seen at the upstream side of a structure. Thus, the results hint at scour at the pier foundations of Pages Road Bridge with erosion reaching scour depths and sediment accumulations in the range of ~ 0.3 m. Such scour depths will unlikely represent a hazard, however, monitoring of scour development should be considered in cases of an increasing occurrence of flood events, and results might be considered for the retrofit of the bridge.



Figure 6-12 Soundings at Pages Road Bridge. Measurements level with the piles are indicated as red circles. Zero corresponds to the eastern lightpost.

Wainoni Road Bridge (Bower)

The Wainoni Road Bridge, or Bower Bridge, crosses the Avon River in an approximately northsouth orientation on the eastern edge of the city, connecting the suburbs of Wainoni and New Brighton. The bridge was opened in 1942.

Original structure

Wainoni Road Bridge is a three span reinforced concrete structure with the deck supported by two concrete wall piers.

Earthquake Damage

The bridge was mainly affected by the Christchurch earthquake, with slumping and minor lateral spreading of the approaches to the bridge. This only has a minor effect on the bridge structure.

Retrofit of structure

There had been no retrofit applied to this bridge at the time of the flood event.

Scour

The soundings shown in Figure 6-13 were conducted only on the downstream side of the bridge only due to traffic. The channel profile appears generally approximately symmetric. Different measurements have been conducted in the vicinity of the pier foundations. Behind the piers, the water depths corresponded well to the general profile, possibly showing some slight sediment accumulation at the southern pier foundations. However, both corners were characterized by significant deepening by 0.3-0.7 m. Approximately 4 m downstream of the southern pier, sediment accumulation of ~ 0.4 m was identified. This was not confirmed at the northern pier. Nevertheless, these results suggest the development of some scour at Bower Bridge. A more sophisticated survey strategy is recommended to investigate the scour and possible related hazards in more detail. The coarse and very simple method presented here is certainly not sufficient to draw any definitive conclusions.



Figure 6-13 Soundings at Bowers Bridge. No measurements were conducted on the upstream side of the bridge due to traffic. Regarding measurements at the pier pile foundations, red circles indicate sounding behind the square piles, green circles at the corner and blue circles ~ 4 m downstream.

Anzac Drive Bridge

The Anzac Drive Bridge, shown in Figure 6-14, is located on State Highway 74 and crosses the Avon River in a north-south orientation. The bridge also acts as a crossing point for a number of utility service lines.



Figure 6-14 Anzac Drive Bridge on 19 April 2014.

Original structure

Anzac Drive Bridge is a reinforced concrete structure which was constructed in 1999. Plan and elevation views of the bridge from the construction plans are shown in Figure 6-15 and Figure 6-16. The bridge has a total length of 48.4 m over three spans (14.9 m-18.6 m-14.9 m) and a total width of 21.7 m.

The superstructure consists of simply supported precast double core units. The superstructure is supported by cast in place wall-type abutments and two four-column bents. The piers are supported by 1.5 m diameter steel shelled reinforced concrete piles 20 m in length, and are not connected by pile caps. Each abutment is supported by grade 300 steel H-piles 22 m in length, with 16 at the northern abutment and 15 at the southern.



Figure 6-15 General plan of Anzac Drive Bridge, with the left of the figure the southern edge of the bridge (CCC, 1999).



Figure 6-16 Elevation view of Anzac Drive Bridge (CCC, 1999).

Earthquake Damage

The bridge sustained moderate to severe damage following the Christchurch earthquake due to liquefaction and lateral spreading, and this was further progressed in the subsequent events, mainly the 13 June 2011 earthquakes.

Both the abutments settled and back-rotated as a result of the lateral spreading in the Christchurch and June 2011 earthquakes. Following the Christchurch earthquake, the northern

abutment developed approximately 4° of back rotation, while the southern abutment to back rotated by 6° and displaced towards the river. There was slight additional rotation of the abutments following the 13 June 2011 earthquakes.

Following the Christchurch earthquake, both pier frames suffered extensive cracking of the concrete columns and beams as well as the beam-column joint regions of the pier cap. Spalling of the concrete cover appears to be primarily as a result of interaction between the transverse motion of the bridge and the rotation of the piers due to lateral spreading. There was no serious damage to the bridge superstructure.

Retrofit of structure

No details of the repair and retrofit approach are available at this stage.

Scour

Figure 6-17 shows the riverbed profile determined from soundings. The riverbed at Anzac Drive Bridge is defined by directing the major part of the flow through the piers. No significant variation in morphology can be observed at the piers. Immediate deepening in front and slightly more at the pier foundations corners can possibly be related to scour, but (i) has no significant impact on channel morphology, and (ii) from this limited data set, cannot be determined if related to scour.



Figure 6-17 Soundings at Anzac Drive Bridge. Only upstream measurements were possible due to traffic.

B) Heathcote River

Heathcote River Bridge



Figure 6-18 Heathcote River Bridge on 20 March 2014.

The Heathcote River Bridge shown in Figure 6-18 is located on State Highway 74 and crosses the Heathcote River in a north-south orientation. The bridge also acts as a crossing point for a number of service lines.

Original structure

Heathcote River Bridge is a reinforced concrete structure which was constructed in 1963. The bridge has a total length of 52 m over three spans and a total width of 10.6 m.

The superstructure consists of 10 prestressed concrete precast I-beams simply supported at the abutments. The superstructure is supported by reinforced concrete abutments and three column reinforced concrete piers and pile cap. The piers are supported by ten 4.32 m vertical octagonal reinforced concrete piles. Each abutment is supported by the same number of raked piles.

Earthquake Damage

The bridge was undamaged during the Darfield earthquake. During the Christchurch earthquake there was a significant amount of lateral spreading and cracking of the approach soils and approach settlement. There was approximately 1° of back rotation of the north abutment towards the river.

Scour

The soundings at Heathcote River Bridge are shown in Figure 6-19 and indicated that most of the flow is going between the two pile groups. No significant water depth variations were noted at the foundations, while downstream a slight deepening in the center of the channel by ~ 0.2 m was observed, likely eroded due to compression of streamlines between the piers.



Figure 6-19 Soundings at the Heathcote River Bridge.

Rutherford Street Bridge

The Rutherford Street Bridge is shown in Figure 6-20 and located on State Highway 74. It crosses the Heathcote River in a north-south orientation. The bridge also acts as a crossing point for a number of service lines.



Figure 6-20 Rutherford Street Bridge on 20 March 2014.

Original structure

Rutherford Street Bridge is a reinforced concrete structure which was constructed in 1983. The bridge has a total length of 39.7 m over three spans and a total width of 18.6 m.

The superstructure consists of 13 reinforced T-beams simply supported at the abutments. The superstructure is supported by tall reinforced concrete abutments and two wall-type piers. The piers are supported by twelve 4.5 m raked octagonal prestressed concrete piles. Each abutment is supported by the same foundation system.

Earthquake Damage

The bridge was undamaged during the Darfield earthquake. During the Christchurch earthquake the high abutment walls rotated and displaced horizontally, closing the abutment joint gaps, and the approach had settled by approximately 0.1 m. Lateral spreading may have been a factor causing this damage.

Scour

The soundings shown in Figure 6-21 highlighted that flow is funneled through the two pier structures, but no indicators for scour were observed.





Lyttelton Port of Christchurch

The GEER team visited Lyttelton Port of Christchurch (LPC) on 21 March 2014 for an update on the port's development after the earthquakes in 2010 and 2011 and to investigate possible flood impacts on the port (Figure 6-22).



Figure 6-22 Google Earth image showing the location of Lyttelton (43° 36' 13.61" S; 172° 43' 9.79" E) in comparison to the city of Christchurch. Additionally, the image highlights Lyttelton's location at the foot of the steep slope characterizing particularly this northern region of the harbour. While the port location offers a great advantage regarding the protection from energetic wave action, heavy rainfall events in conjunction with steep slopes might represent a hazard here.

Port Overview

LPC is the NZ South Island's biggest port and documented 525 ship visits and the handling of 185,748 Total Container Volumes (TEUs) in the second half of 2013. The port was able to sustain its steady increase in revenues (6.4%) to \$57.6 million (July-Dec 2013). This highlights the performance success during and post-earthquakes, despite the immediate vicinity to the epicenter of especially the 2011 earthquake and significant damages to port structures. The port has specialized facilities for containerized cargo, coal, fishery products, forestry products and petrochemical products (LPC, 2005). The layout of the main wharves at the port is indicated in Figure 6-23. Prior to the Canterbury earthquake sequence the majority of this cargo was handled on the four Cashin Quay wharves. The Z berth was used by the fishing industry, the Oil Wharf by the petrochemical industry, and the remainder handled dry bulk, vehicles and passengers. All wharves are supported by vertical pile foundations that are constructed of hardwood timber, reinforced concrete or steel tubes.



Figure 6-23 Layout of Lyttelton Port of Christchurch highlighting the main wharves (Ragued et al. 2014).

Earthquake Damage

The port was initially damaged during the Darfield earthquake, with subsoil movements resulting in settlement and lateral deformation. In the main port area these movements were attributed to a slope failure in the soft clay and silty sand layers, and were not believed to be due to any liquefaction effects. However, liquefaction and lateral spreading in the Oil Terminal area affected the Oil Wharf, tanks and pipe work.

More significant movements and damage to wharves, breakwaters, quays and reclaimed land occurred as a result of the Christchurch earthquake, with up to 0.5 m of vertical movement and 1 m of lateral movement recorded. There was further significant movement and damage from the 13 June 2011 earthquakes. Cashin Quay moved seaward, and piles, beams and tiebacks fractured. Paved areas were cracked due to lateral movements, and container cranes were knocked off their rails. Following the June earthquakes, temporary stabilization works were put in place. Wharf damage at Z berth mean that it could not be used following these events.

After the earthquakes the port was operating with a third less land in the Cashin Quay area due to the damage and repair works. Despite the severity of the earthquakes, the port was basically operational within hours following the Darfield earthquake, and within 96 hours following the Christchurch and 13 June 2011 earthquakes (LPC, 2011).

Port development post-earthquakes

A mediation process with the port insurers concluded in December 2013. A settlement of claims arising from earthquake damage involves the payment of \$450 million (gross). An amount of \$66 million has already been expended on keeping the port operational after the earthquakes, while the remaining funds will be invested in future port development. The extended mediation process also contributed to the fact that some earthquake damage was still visible during the NZ-GEER team visit in March 2014 (Figure 6-24).



Figure 6-24 Example of visible earthquake induced damage to Cashin Quay in March 2014.

Early development of the port structures after the earthquakes has been mainly focused on the Te Awaparahi Bay land reclamation shown in Figure 6-25 and the investigation of engineering strategies to stabilize Cashin Quay wharves 1-3 (Figure 6-22). For the latter, stabilization with piles to sustain a vertical port wall or a sloped rubble-mound support structure have been considered. The Te Awaparahi Bay land reclamation has already reached an expansion of 5 hectares using reusable rubble from demolitions in Christchurch, half of the 10 hectare initial target (Figure 6-25 and Figure 6-26). The gained land will offer the required space for a further increase in shipping activities, and arguably offered an adhoc solution for demolition material from Christchurch once the reclamation had overcome legal issues arising from initial emergency, uncleaned and uncontained reclamation works and the decontamination and

containment of fill was sorted out. Further planned developments will include the expansion of cruise boat tourism in LPC.



Figure 6-25 Planned area of reclamation in Te Awaparahi Bay (LPC, 2011).



Figure 6-26 Te Awaparahi Bay land reclamation area on 21 March, 2014.

Impact of March 2014 flood

Most of the port structures were not affected by the flood. However, Figure 6-27 shows two tanks damaged by debris from a slope failure below Brittan Tce on the afternoon of March 5th. This landslide initiated during the heavy rainfall event.

The debris from the landslide damaged one tank storing 1.2 million liters of jet fuel, leading to a leak that forced the evacuation of 19 households in the immediate area and closure of nearby roads. This evacuation was in place for two days while fumes dissipated and some of the fuel was pumped into other undamaged tanks. The majority of leaked fuel was captured in the concrete walled containment area around the tank. Some of the leaked fuel entered the stormwater system and was released into the harbor before the spill could be contained.

Another tank also storing fuel was dented by the slope failure debris, but its contents were not affected.

Another slope failure above Simeon Quay resulted in structural damage to a substation that supplied power to the port, which could have cut power to the port if the failure progressed. However, the slope failure did not progress and this was avoided. The port had backup generators in place to run basic port functions.



Figure 6-27 Tank impacted by landslide that initiated during periods of heavy rainfall.

Concerns were expressed regarding the safety issue and current closure of (Old) Sumner Rd. These roads represented an alternative access route to Lyttelton and the port in the case of tunnel closure. Significant destabilization of the steep slopes along these roads as shown in Figure 6-28 made them a major safety issue and led to closure. An alternative trucking route to the port is highly desired as a backup to the tunnel. The tunnel entrances are subject to risk of closure due to landslides, which risk may even increase during heavy rain events. If it came to a flood in the tunnel at the same time, the port could theoretically become inaccessible. No such observations were made during the flood and heavy rainfalls in March 2014, but it was mentioned as a possible concern related to flood and heavy rainfall events.





Lyttelton stormwater failure

The over topping of the storm water inlet shown in Figure 6-29 at the top of Canterbury Street in Lyttelton led to progressive failures downstream during the March 5th flood event. This storm water inlet is at the top of the drainage system and collects water that flows off the top of the Port Hills in an undeveloped section above Lyttelton. The GEER team found the culvert unplugged and free flowing at the time of its field reconnaissance. Evidence was found that the inlet became plugged at some point during the storms leading to overtopping of the collection basin and undermining/erosion downstream of the inlet structure as shown in Figure 6-29b.



(a)

(b)

Figure 6-29 Storm water inlet at the top of Canterbury Street that was overtopped during the March 5th event (Canterbury Street: -43.596225°, 172.723001°).

Water then eroded the pavement and base course exposing the storm water pipe as shown in Figure 6-30a. As shown in Figure 6-30b, the erosion of pavement and the base course continued down Canterbury Street. Repairs to the streets shown in Figure 6-30c had been made at the time of the GEER team's reconnaissance.







(c)

Figure 6-30 Erosion as a result of the storm water inlet in Figure 6-29 overtopping. (Photos (a) and (b) courtesy of Michael Hayes) (c) Canterbury Street restored to grade (93 Canterbury Street: -43.596590°, 172.722847°).

Further down Canterbury Street, water eroded the retained earth and street above a retaining wall shown in Figure 6-31, which had previously failed and been replaced in 2013 by SCIRT. The new retaining wall consists of a wet cast block. As shown in Figures 6-31c and 6-31d, the drainage system behind the wall was found to be plugged at the time of the GEER teams visit on March 22, 2014. SCIRT reported that the wall was found to be safe. GEER found no noticeable horizontal wall movement. SCIRT also reported damage to a new retaining wall being constructed on Sumner Road as a result of the flood event.







(b)



(c)

(d)

Figure 6-31 (a) Storm water flowing over the Canterbury Street retaining wall. (b) Erosion of Canterbury Street and retained earth above the wall. (c) and (d) plugged drains directly behind the wall as a result of upstream erosion seen in Figure 6-30 (a and b). Photos (a) and (b) courtesy of Michael Hayes (73 Canterbury Street: -43.599005°, 172.722243°).

GEER found evidence of numerous plugged inlets to the storm water system such as that on Selwyn Street in Lyttelton, shown in Figure 6-32. In interviewing the local community GEER found that locals unearthed the plugged inlets to enable the runoff to enter the storm water system. The Selwyn Street example in Figure 6-32a and b shows a small slump that fell from above the drainage inlet and plugged it resulting in the flow being routed down Selwyn Street instead of into the storm water system.

It's plausible that had the culvert not been unplugged during the storm event that water pressure behind the walls in Figures Figure 6-32c and Figure 6-32d could have resulted in failure, or failure of another type further downstream. A previous landslide below the sheet pile wall in Figure 6-32c had occurred prior to the 2010-2011 Canterbury earthquake sequence resulting in damage to the home below which is no longer present.











(c)

(d)

Figure 6-32 Unplugged culvert on Selwyn Street above crib retaining wall, Photo courtesy of Michael Hayes (a). Post cleanup by CCC at the drain inlet (b). Previous slope failure and

installed sheet pile retaining wall (c) adjacent to crib wall with culvert out let picture left (d) (17 Selwyn Road: -43.598748°, 172.716026°).

Avon River stop-banks

Before the Canterbury earthquake sequence, the crest level of the majority of stop-banks were at a river level (RL) or stage of 11.2 m (CCD datum). Along Hulverstone Drive in Avondale, the stopbank crest level was at 10.9 m (Harris, 2003). The 11.2 m RL was based on a 1% annual exceedance probability storm surge event with 0.2 m of freeboard (GHD 2012). The crest level for much of this system was at a similar elevation as the residential areas surrounding the river.

Although subsidence occurred as a result of the Darfield earthquake along the Avon River the majority occurred as a result of the Christchurch earthquake. As a result of that subsidence, CCC constructed a new system of stop-banks along both sides of the river from the edge of the CBD to the mouth of the Avon River to the east. In some locations, stop-banks had to be built over a meter above the ground level of the surrounding areas.

Prior to a pergiean spring side or king tide event in July 2011, more than 11 km of stop-banks were built up to a 10.8 m RL along the Avon River in four days. A silty gravel was used for construction, as this was easily accessible and was reasonably impermeable. In some areas sand bagging was used as a temporary means of flood control. Due to the time constraints imposed by the king tide event, no improvement of the soils below the stop-banks could be carried out to mitigate the effects of liquefaction and lateral spreading in future earthquakes. These new stop-banks were damaged multiple times during the most severe aftershocks. This system of temporary stop-banks performed reasonably well during the king tide event.

Following the emergency king tide event in July of 2011, the stop-banks were restored to a RL of 11.2 m. The primary design used 3:1 or 4:1 battered slopes with a 2.5 m wide top where space was available. When space was limited along the river's edge diamond block walls and reinforced earthen walls were used in place of the stopbank design.

During the March 5th flood event the Avon River stop-banks performed as expected by CCC. The March 5th flood event also happened to coincide with a pergiean spring tide which caused flood waters to be retained behind the stop-banks once the river level had dropped below the flood water level. This posed a lack of drainage which may extend or exacerbate a flood depending upon the duration and intensity of the event.

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7. PERFORMANCE OF LIFELINE SYSTEMS DURING 5TH MARCH 2014 FLOODING

The lifelines suffered severe damage after the 2010-2011 Canterbury earthquake sequence. Repair to the lifelines begin immediately following the Darfield earthquake. After the 22nd February 2011 Christchurch earthquake repairs to the water, wastewater and stormwater systems were turned over to the Stronger Christchurch Infrastructure Rebuild Team (SCIRT).

The GEER team followed up on the performance of the lifelines following March 5th flood event.

Water Supply

The City of Christchurch, City Water & Waste Unit (CWW) owns, operates, and maintains the Christchurch water and wastewater (WW) systems. This section described the water system and the next section describes the WW system.

The Christchurch water supply system relies on groundwater wells, pumps and reservoirs located within the city. The CWW Unit Manager, Mark Christison, informed the team that the Christchurch water supply system performed well during the event with no loss of service to customers. At the time of the reconnaissance, the post-earthquake pipe repairs for the water supply system were 64% complete. 33% of pumping stations have been repaired (SCIRT, 2014). As a result of the on-going repairs the system is now largely stable.

Immediately following the 5th March storm, microbial testing of all the wells and reservoirs was carried out and only one well on Colombo Street had *Escherichia coli* (E.coli) present. The well was immediately isolated and further testing is still in progress. CCC's knowledge to date indicates that a sampling problem may have been the cause of the E.coli due to the well head being under flood water at the time of sampling. The investigation is ongoing. Apart from this one well being shut down due to a positive E.coli test, the water supply network performed more than adequately during this flood event.

Wastewater

The WW network is mainly a gravity type design with post-earthquake repairs changing some components of the network to pressure and vacuum systems. There was no loss of service to customers attributed to the flood. SCIRT's post-earthquake rebuild of the wastewater pipe network is 35% complete and the pumping stations are 48% complete (SCIRT, 2014). Repairs still need to be carried out in both the western and eastern portions of the city, but were not

adversely affected by rainfall or flooding. There was expected surcharging from various points around the city from sewer manholes which posed a health risk to residents.

The CCC Asset Network & Planning team modelled the predicted surcharging from manholes, under urgency on 6th March, as seen in Figure 7-1. This model prediction was then used in the response as an indicator for where the WW maintenance crews should go to clean up the effects of surcharging WW and inspect/replace manhole covers. This prediction was used in conjunction with WW related geospatially located phone calls placed to CCC in the March 5th event as seen in Figure 7-2, noting that phone call data from a prior flood event in June 2013 was used as a comparison. Specific mention should be made of the Southwest area of Christchurch in Figure 7-1 which the model predicted to have surcharging but which experienced substantially less, most likely due to recent WW project completions.

There was an observed increase in the inflow to the wastewater treatment plant (WWTP) which has a maximum capacity of 7.5 m³/s. The inflow recorded during the event was just under 7 m³/s. The average dry weather inflow at the WWTP increased from 1.8 m³/s to 2.6-2.7 m³/s following the 2010/2011 earthquake sequence. This is mainly due to water infiltration through damaged pipes into the network. SCIRT, who is responsible for rebuilding these networks, indicates appreciable differences in the inflows into the WWTP will be observed when the entire catchment is repaired/rebuilt in early 2015.



Figure 7-1 Prediction modelling of a 1 in 10 year rain event effects on the wastewater system in Christchurch, used as a guide only for the 5th March event, source R. Meek (personal communication, 7th April 2014).



Figure 7-2 Location of WW related received calls taken by the CCC call centre during the event with calls from a previous large rainfall event in June 2013, R. Meek (personal communication, 7th April 2014).

A large terminal pump station located in Pages Rd that is responsible for directing 35% of the city's WW to the WWTP suffered extensive damage in the earthquake sequence as seen in Figure 7-3. The pumping station moves wastewater via two 1.2 m diameter pipes to the WWTP, but currently is only pumping through one new Glass Reinforced Plastic (GRP) 1.2 m diameter pipe. The conveyance capacity in this part of the network has been reduced by 50%. The WWTP had available capacity that was unable to be utilised during the flooding which caused overflows to be activated into the Avon and Heathcote river systems and the estuary in line with normal business process.



Figure 7-3 Currently damaged Pages Road gravity pump station (-43.513658°, 172.709793°). View from new gravity pump station construction site opposite. Photo courtesy of Dave Holland.

Due to the extensive coverage of the flood water some sewers were adversely affected while others were not. Gravity sewers in the worst flooded areas were surcharged through the manholes. The WWTP oxidation pond contents are discharged in to the ocean, three kilometres offshore, via the ocean outfall pump station and pipe which was running at design capacity of 5.5 m^3 /s during the event. The oxidation ponds, downstream of the WWTP, still had capacity for this event and were able to accommodate the 1.5 m^3 /s differential between the WWTP outflow and flow through the outfall. Overall, the wastewater system performed as expected, with minor surcharging, given the extent and severity of the flood water coverage with service to customers expected to improve as entire catchments have upgrades and repairs completed.

Christchurch Stormwater

An interview with Mr. Tom Parsons and Mr. Graham Harrington from Christchurch City Council (CCC) was conducted for information on the performance of the stormwater system on 5 March flood event.

The Christchurch stormwater network is planned and operated by CCC. It is mainly a gravity system which involves conveyance of surface runoff through sumps, pipes, open channels and rivers to the discharge outlet at the Avon Heathcote Estuary. The city is divided into five river catchments: the Avon, Heathcote, Styx, Otukaikino and Halswell.

Much of the stormwater pipe network capacity is designed for a 5 year recurrence interval event. Flood water exceeding this level is conveyed through the secondary flow paths which include the roads, waterways and swales. The pipes suffered earthquake-induced damages such as breakages, cracks, liquefaction blockages from sand infiltration, collapses, and loss of gradient (SCIRT, n.d.). The capacity of the open channels and waterways have been reduced to some degree due to lateral spreading (up to 6 m in one cross-section of the Avon River), subsidence of stopbanks, and changes in river beds and gradient, which are addressed in Chapters 3 and 5.

The stormwater team at CCC receives meteorological information from MetService. The 3day and hourly rainfall forecast and rain radar information are analysed to determine the magnitude of the expected storm in terms of return period. At 5 pm on 4 March, the storm was expected to be a 5 year event. In advance of the storm, standard flood management activities were employed. All gratings and critical inlets were checked prior to and during the event, to the greatest extent possible. Additional measures were also undertaken during the event, but given the short advance notice of the storm, there was no time for event specific flood preparation. The normal mitigation strategies that were employed would have made very little change to the flooding observed, except for some localized conditions such as the Lyttelton overflow described in Chapter 6, as the intensity and duration of the storm far exceeded the overall network capacity.

The magnitude of the 5 March event was significantly greater than what the stormwater pipes and the open flow networks were designed for. Therefore, city-wide flooding was experienced, especially in the low-lying areas and floodplains. In particular, as shown in Figure 7-4 the very low-lying flood-prone Dudley Creek catchment suffered the greatest. The water level survey data obtained on 5 March has been used to determine the number of houses that may have flooded.

The flow through the Avon River is believed to have been restricted by earthquake repair works. Scaffolding under the Colombo Street Bridge impeded flows and may have increased flooding in the central city. No other instances have been reported of bridges blocked by debris. The effect of restriction of rivers on the extent of the flood will be analysed in the future using data collected for the flood debris along the Avon. Also, the city's river models will be tested and calibrated using actual precipitation data from many rain gauges and the observed extent of the flood.

Despite the high intensity of the storm, the stormwater system did not suffer any significant damage. The flat topography of Christchurch means that the overland flow velocity is low, thus the damage that the flood water can do to the stormwater network is minor. Scour from high energy waters from small but steep catchments in the Port Hills is possible, and some instances of damage were reported as exemplified in Chapter 6.



Figure 7-4 Dudley Creek overflowing on to Stapletons Road (-43.509433°, 172.655949°) and footbridge in Richmond, Christchurch. Photo courtesy of Su Young Ko.

Road Network

As a part of the traffic management plan, Christchurch City Council's Land Drainage and Roading teams closed off some roads in Mairehau/Richmond area in the evening of 4 March. The list of road closures grew longer by the morning of 5 March as increased surface flooding was observed from persistent rainfall and high spring tide. The flooded streets were mainly in the eastern suburbs: New Brighton, Avonside, Wainoni, Bromley, Linwood, Central City (Figure 7-5), Edgeware (Figure 7-6), Richmond (Figure 7-7), St Albans, Shirley, Mairehau and Opawa. Some streets in the Port Hills were also closed off due to concerns of slope instability. After the retreat of flood waters, storm debris and new potholes on the roads presented traffic hazards to travellers (Christchurch City Council, 2014).



Figure 7-5 Avon River overflow causing surface flooding on Fitzgerald Avenue (-43.524078°, 172.650935°), Central City, Christchurch. This road demonstrates a postearthquake reconstruction design error. The road should have been built at a higher elevation to avoid flooding. Photo courtesy of Su Young Ko.



Figure 7-6 Road closure due to temporary traffic management – Geraldine Street (-43.515579°, 172.647506°), Edgeware, Christchurch. Photo courtesy of Su Young Ko.



Figure 7-7 Warning sign for flooded streets – Warden Street (-43.510297°, 172.655095°), Richmond, Christchurch. Photo courtesy of Su Young Ko.

Telecommunications Network

Information on the flood impacts to the telecommunication network was obtained from an interview with Mr Rob Ruiter from Chorus. Chorus is the largest telecommunications utility company in New Zealand.

Chorus provides high capacity internet and communication services to Christchurch. There are three types of network cables: the older paper and lead copper cables, modern plastic copper cables and fibre optic cables. Most of the high capacity cables are either in 20 mm, 50 mm or 100 mm ducts in the ground which provides extra level of resilience and easy access to faulty portions of the network. The telecommunication network has been designed to be inundated. The 5 March flood caused problems for cables that probably had some damage from the earthquakes, but were not manifested as faults. Some paper and lead copper cables were damaged from earthquake induced land movement. These cables were laid from the 1920s and the old and brittle lead sheathing cracked at the neck of the joints under the tensile forces experienced by the land movement. Flooding and the high groundwater table (as a result of rainfall) have caused water to enter into the cables through the cracks and resulted in faulting.

Figure 7-8 shows where the major cable fault locations occurred in Bexley, New Brighton and Beckenham as a result of the flooding. Access to some of the sites was not possible because large portions of these suburbs were inundated to depths of 1.5 m.
Approximately 600 customers lost service for about 3 to 4 days until the flood water receded and the access was gained for repair.

There was no damage to plastic copper cables and the fibre optic lines as a result of the flood event. Plastic copper cables are greased with plastic sheathing which repels water. The fibre cables are intrinsically water resistant.

The failure of the electricity connection to Banks Peninsula (operated by Orion) for 2 to 3 days meant that an alternative power source had to be provided to the Little River exchange (

Figure 7-8). High flood waters blocked the streets; however, a large transporter was engaged to deliver the generator to the site and the service was regained. Both Akaroa and Mt Pearce exchanges ran on their own generators during the power outage. Visits were made to outlying radio stations and cabinets to replace the batteries or to apply portable generators.



Figure 7-8 Map showing the locations of major telecommunication cable faults in Christchurch and Banks Peninsula (Google, 2014).

Waste Disposal

The GEER team contacted Canterbury Waste Services (CWS) which owns and operates the Kate Valley Landfill and the transit stations for waste disposal services within the Canterbury region (2014). CWS did not see an increase in tonnage delivered to the landfill as a result of the March flood event. CWS did note that additional business was generated for waste hauling companies providing skips and containers to affected households. Upon request of Christchurch City Council CWS provided additional kerbside mobile garbage bins to the affected neighbourhoods.

Gas Distribution System

Contact Energy (Rock Gas) who operates the natural gas pipeline system in Christchurch and is owned by Contact Energy was contacted by the GEER team (2014). The pipeline gas network and feeder plants suffered no damage as a result of the flooding and the systems performed well. Rock Gas has upgraded internal communications equipment as result of the performance of their public band UHF radios during the post-earthquake shutdowns. Rock Gas intends to operate now using the Team Talk which is a lifeline communications provider, which is already in use by Rockgas's LPG cylinder distribution network of trucks and will be utilized by other parts of the company in the near future.

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8. POST-EARTHQUAKE SEQUENCE FLOODING IMPACTS ON THE BUILT-ENVIRONMENT

In early 2014 Christchurch had the heaviest sequence of rainfall since the 1970s. Several large rainstorms fell in the city, saturating the ground, raising river and stream levels, and flooding homes, properties and streets. In many locations flooding was made worse by the effects of the 2011 Canterbury earthquake sequence (CCC Task Force 2014a), which had caused land to slump by up to half a metre in some areas, reducing capacity in many waterways, and damaging the pipe and outfall infrastructure (see Chapters 3 and 5 of this report for further details).

At a request from Christchurch Mayor Lianne Dalziel, the Christchurch City Council (CCC) set up the Mayoral Flood Taskforce (hereinafter "the Taskforce") on 29 April, 2014 with the aim of finding immediate/short-term solutions for those residents severely impacted by the flood waters. The Taskforce started work on 1 May, 2014 with members from Council staff, engineering consultants, the Stronger Christchurch Infrastructure Rebuild Team (SCIRT), Environment Canterbury (ECan), the Canterbury Earthquake Recovery Authority (CERA) and the Earthquake Commission (EQC). The Taskforce was asked to report to the Council on 12 May, 2014 with a range of temporary solutions that would help reduce or defend against flooding in the near future. Taskforce field engineering teams carried out an area-by-area analysis of the causes and scope of flooding problems in the following priority areas located in Figure 8-1a: Lower Avon River; Dudley Creek (Flockton); Lower Heathcote (including Woolston/Opawa); Upper Heathcote; Heathcote Valley Southshore; Sumner (including Redcliffs); Little River; and Lyttelton. The Taskforce field teams: a) identified the flooding issues; b) quantified the effects of earthquake damage; c) assessed frequency of inundation above or below floor level; d) and designed appropriate house defence or local area scheme. Details of the findings from the Taskforce work are presented in the CCC Task Force (2014a) report and related Appendixes (CCC Task Force 2014b; CCC Task Force 2014c).

This section focuses on the 5th March, 2014 flood impacts and on the concomitant and combined earthquake-induced contributing impacts. Attention is given therefore to the Taskforce findings related to: flooding issues¹; effects of earthquake damage; and frequency of inundation above or below floor level. The presentation and discussion of the temporary flood defence measures, i.e. immediate/short-term solutions suggested by the Taskforce to the residents is beyond of the scope of this report (technical details can

¹ Note from Taskforce report (2014a): The Taskforce field teams had only five days to carry out all of the above work, so engineering judgement and interpolation was necessary. However the Taskforce considers the process was sufficiently robust to give a high level of confidence in the key findings.

be found at CCC Task Force 2014b). The focus is on areas where earthquake-induced geotechnical and tectonic impacts on flooding where discussed by the GEER team in Chapter 5, namely in the areas of: 1) Lower Avon River (Figure 8-1b and dark green boundary in Figure 8-1a); 2) Dudley Creek, Flockton area (Figure 8-1b and purple boundary in Figure 8-1a); 3) Lower Heathcote (Figure 8-1c and dark yellow boundary in Figure 8-1a). These areas suffered the most severe flooding after the 5th March event as shown in Figure 8-2.







Figure 8-1Areas of investigation by the 2014 Mayoral Flood Taskforce (CCC Task Force, 2014a): (a) Summary map of Christchurch outlining investigation areas; (b) Avon River area of investigation; (c) Heathcote River area of investigation.



Figure 8-2 Observed Flooding in Christchurch March 2014 with hind cast model predictions (courtesy of Tonkin & Taylor, 2014).

Lower Avon River

Flooding history, existing flood protection and key drainage infrastructures

Stopbanks were first constructed along some lengths of the Avon River in the early 20th Century. During major storm events the river has over topped its banks leading to progressively higher and longer lengths of stopbanks. Stopbank over topping during the 1992 snow-storm resulted in a major extension of the stopbank system (see more details in Chapter 2). The area shown in Figure 8-3 is protected by the Avon River stopbanks and back flow protection devices on the stormwater network outfalls. There are numerous drainage pipes and open drain outfalls to the river, including discharges from three pump stations (CCC Task Force, 2014b).

Earthquake-induced tectonic-geotechnical effects and impacts on drainage and key infrastructures

Figure 8-3 shows the Lower Avon River area that was declared Residential Red Zone (RRZ)2 area after the 2010-2011 earthquake sequence. This area suffered significant ground settlement as a result of the earthquakes and is now typically at river level (RL)10.0 – RL11m. Vertical and horizontal ground movements in the range of -0.1 m to -0.5 m have been observed along the Avon, with some localised movement of -0.5 m to - 1.0 m. As described in Chapter 3, moderate to significant liquefaction accompanied by moderate to severe lateral spread occurred along the length of the Lower Avon River and within the RRZ. The riverbed experienced heaving. Some parts of the RRZ area are now below annual high tide level and the river flood level for moderate to major storm events (CCC Task Force, 2014b).

The Avon River banks suffered significant slumping as part of liquefaction and lateral spreading. Temporary stopbanks were reconstructed along the river's edge. Each major earthquake event caused further damage and settlement to the stopbanks. These stopbanks continue to suffer from bank slumping and fill consolidation. This results in portions of the stopbanks being lower than the river flood level.

Also the hydraulic head necessary for the local stormwater network to function as originally designed has been reduced, thus reducing the stormwater network's efficiency.

The local drainage network suffers from a reduction in capacity during peak river levels due to ground settlement. Additionally, the emergency response placement of the stopbanks inadvertently covered some storm drain manholes and sumps causing local drainage issues.

² Land designated after the February 2011 Christchurch earthquake for government purchase and clearing (<u>http://cera.govt.nz/residential-red-zone</u>). See Chapter 9 of this report for further information



Figure 8-3 Lower Avon River: boundary of the area analysed by the CCC Taskforce and extent of March 2014 flood (map from CCC Task Force 2014b).

March 2014 flood extent

Flooding along the urban side of the stopbanks was caused by both: (1) the river floodwaters back flowing through the flap valves and (2) rainfall within the catchment (i.e., behind the stopbanks) not being able to drain into the river.

The river also over-topped the stopbanks in some locations. Bank overtopping occurred as a result of stopbank slumping and settlement and the flooding in these areas was exacerbated by post-earthquake maintenance practices of blocking off some piped stormwater outfalls. The blocking of outfall been undertaken primarily because: (a) postearthquake stopbank restorations required some manholes to be covered and as a result prevents access to flap gates for maintenance; or (b) to prevent backflow from the river, but this resulted in surface ponding.

March 2014 flood impacts on the built-environment

The CCC Task Force did not investigate property level flooding for this specific area since the area is classified as RRZ. However, using GIS to overlay property map with the

flood extent along the Avon River indicates about 396 properties experienced some flooding. Most of these properties would have been abandoned and likely demolished because they are in the RRZ, however not all homes have been abandoned. 120 houses in the RRZ were reported as flooded by the owners/residents, and 8 garages were confirmed as flooded outside the RRZ area. A number of properties also reported flooding up to the house foundations.

Dudley Creek (Flockton Area)

Flooding history, existing flood protection and key drainage infrastructures

The Dudley Creek catchment shown in Figure 8-4 has a history of flooding. Floods have been documented across the area dating back to the early 1900's. The area was then occasionally flooded up to the 1970's, until the Dudley Creek Diversion was constructed (Chapter 2) to divert floodwaters from the upper catchment to Horseshoe Lake, which had effectively controlled flooding up to present. Residents, who have lived in the area for 30 years, reported there was no flooding to the area before the 2010-2011 earthquake sequence. After the earthquakes, there have been several floods in the area, namely August 2013, June 2013, March 2014, April 18th and 30th 2014 (CCC Task Force, 2014b).

Dudley Creek and its tributaries are demonstrably under capacity in rainfall events both within the open channels and at culverts. One of the most vulnerable areas with the Dudley creek catchment is around Flockton Street, which has the general low-lying topography of a basin and during flood events often suffers from significant ponding. Underground infrastructure helps to drain this ponding; however, many of the water levels within the structure rely on hydraulic pressure. The Flockton Invert, located on Harrison Street, is a submerged pipe and water levels equalize with the Dudley Creek, which then results in a water level in the Flockton area being higher than the ground level because the Dudley Creek bank height is at the outlet invert (CCC Task Force, 2014b). There are no stopbanks or flood defences in the Dudley Creek catchment.

Earthquake-induced tectonic-geotechnical effects and impacts on drainage and key infrastructures

A large proportion of the catchment has subsided between 200 and 500 mm (Chapter 3 and Chapter 5). Bed heave has occurred extensively along Dudley Creek and its tributaries and a subsequent loss in hydraulic capacity has occurred (Chapter 3). Damage to culverts and failure of timber retaining structures has occurred across the lower catchment. Culvert repairs and replacements are proposed by SCIRT, and CCC has been undertaking remedial works, such as silt clearance, since the earthquakes. Further damage to the drainage infrastructures is being addressed through the SCIRT programme as described in Chapter 7.



Figure 8-4 Dudley Creek location plan: boundary of the area analysed by the Taskforce; extent of March 2014 flood and location of flooded houses (map from Task Force, 2014b).

March 2014 flood extent

Figure 8-4 shows the extent of recorded pluvial floodwaters recorded from the March event, which exceeded 600mm in depth in some areas. Flooding in the Dudley Creek catchment resulted from the previously described under capacity waterways, which restrict flows causing water to back up in heavy rainfall. Additionally, flooding is enhanced from the significant seismic-induced ground settlement coupled with the waterways suffering from lateral spreading and bed heave. The inability of the waterways to convey flow has a direct impact on the ability of drainage infrastructure to function. Fluvial water backflows the associated piping and spills into the Flockton area exacerbating pluvial flooding issues.

March 2014 flood impacts on the built-environment

The Flockton area flooding caused an estimated 97 properties to experience water intrusion above floor level at locations shown in Figure 8-4. This number of flooded properties was based on GIS data and the surveyed flood extent. For the wider area, the majority of properties experienced flooding across the section or under foundations.

Vehicles were also flooded and suffered damage. Local evacuations were required due to the risk of residential flooding.

Lower Heathcote

Flooding history, existing flood protection and key drainage infrastructures

The Heathcote River Flood Plain Management Strategy (1998) highlights the historic flooding of 73 houses before 1998 at least on four different occasions (i.e., 1968, 1975, 1977, and 1980). Works previously undertaken to mitigate flooding risk included: widening and deepening of the river channel and dragline operations on several occasions since 1920s; construction of the Woolston Cut (1986) to provide a more efficient flow of water; installing Woolston Tidal Barrage (1994); construction of the Wigram East Retention Basin; raising of 19 homes from 1983 to 1998. Since construction of the Woolston Cut and the tidal control stopbanks (RL10.8m) the Heathcote River tidal and flood flows were mostly contained within the riverbanks.

The local stormwater drainage network within the areas adjacent to the river consists of both road drainage and large catchment drainage such as Tennysons Drain. Drainage outfall diameters range from DN150 to above DN2100. Some outfalls in the lower reaches have flapgates to prevent river and tidal backflow. Local sumps and gravity piping to the Heathcote River with double flapgates, installed in some areas to prevent river and tidal backflow, historically protected Lower Heathcote properties.

Although flooding had previously been experienced in the catchment, a number of residents in the area indicated that there had been no previous flooding on their properties prior to the earthquakes (CCC Task Force, 2014b). After the earthquake sequence, it is fairly common for riverside properties in this catchment to experience shallow flooding or have restricted access during large rainstorms. Three severe rain events from March 2014 to April 2014, have resulted in the recent floor level flooding in the area, along with widespread road, property, and ancillary buildings flooding. Figure 8-5 shows flooded areas from the March 2014 event.



Figure 8-5 Lower Heathcote: boundary of the area analysed by the CCC Taskforce; extent of March 2014 flood and location of flooded houses (map from CCC Task Force 2014b).

Earthquake-induced tectonic-geotechnical effects and impacts on drainage and key infrastructures

LiDAR mapping from CERA (2014) indicates that there has been both land uplift and settlement over the Lower Heathcote Area. The Lower Section of the Heathcote River is tidally influenced and is reported to have risen by up to 400mm, while the upstream portion of the river has settled by 100-300mm. This has resulted in a flatter hydraulic grade reducing the hydraulic capacity of the River and leading to increased bed levels. The River is beginning to re-establish lower inverts in the downstream section.

The Heathcote River has sustained earthquake damage with lateral spreading, siltation and bed heave reducing the capacity of the river system. Surveys undertaken between Garlands Road and Radley Street in May 2014 indicates that there has been some localized reduction in tide bank heights; the design level for this bank (1986) was set at 10.9 mRL, however the survey indicates that approximately 20% of the banks have lower levels than designed, with some areas now having a level as low as 10.4 m RL.

Recent rock movement, slope cracking and slumping in the Port Hills has resulted in additional silt loading on the River and consequentially increased bed levels. The area

also had extensive liquefaction and pipe damage (wastewater and stormwater), which has resulted in additional silt and sand loading.

Condition assessment reports indicate more damage to the stormwater network closer to the Heathcote River and on older drainage systems. Some wastewater repairs have been undertaken. However stormwater drainage repair is still in construction or planned within the next three years, these are mostly repairs and relays of existing pipe capacities.

SCIRT assessment of the drainage infrastructure indicated that there was some damage to outfall pipes. This damage is currently being assessed and some of the outfalls are highlighted for repair. The drainage outfall flapgates are in need of maintenance and residents indicate that backflow is the primary cause of flooding in some areas of the downstream section of the River, indicating that the valves are not operating as designed.

March 2014 flood extent

A moderate to high intensity rainfall over more than 24 hours caused flooding from the 5 March 2014 storm. However, the storm also had strong winds, which broke tree branches and uprooted trees. These and other debris partly blocked channels and screens on stormwater intakes and contributed to higher flood levels. In the Lower Heathcote non-return valves were kept partially open with debris allowing water to flow into the stormwater system and contribute to flooding behind the stopbanks. Residents reported the flooding initially came from the street sumps indicating the flap gates no longer operated correctly. Visual inspection of the flap gates indicated that they no longer fully closed and allowed the river water to backflow into the drainage system.

The storm coincided with a storm surge nearly 0.5 m above the expected tide elevation due to barometric and wind set-up effects. This combined with earthquake repairs in several streams (namely the Colombo Street Bridge) and sewer repairs in the Lower Heathcote caused higher flood levels in these rivers. In summary, tidal influence and local rainfall intensity and localised stormwater flooding (due to inability of stormwater to enter the river) were the main causes of flooding during the 5th March event in the Lower Heathcote area. As seen in Figure 8-5, river flooding was seen along the lower reaches of the Heathcote River and the streets adjacent to the river banks.

March 2014 flood impacts on the built-environment

Flooding depths varied along the length of the Heathcote River; depths were anecdotally recorded from 300 -1000mm on properties. 19 properties were identified as flooded 'Above Floor Level' in the Lower Heathcote area. However, LiDAR contour maps predict that unrecorded flooding exists in the same area.

Flooding 'Above floor level' has resulted in damage to houses and contents. Property damage includes flooding of cars and garages.

The flood depth on the road corridor was too deep for vehicle passage and resulted in isolation of residents. Restricted access to property increased the feeling of vulnerability among residents.

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9. ROLE OF GOVERNMENT ENTITIES AND FUTURE FLOOD MANAGEMENT POLICY CONSIDERATIONS

The purpose of this chapter is to understand the impact of the 2010-2011 Canterbury Earthquake Sequence (CES) on subsequent flooding in the Canterbury region through a multi-hazard and government policy framework. The chapter has three parts. The first part presents the relevant government authorities and agencies involved in addressing flood hazards in some way, in particular concerning the potential increased vulnerability to flooding caused by the CES and the recent flooding problems that parts of the region experienced in March and April 2014. The second part is an analysis of the flooding governance and management problem at hand. The final part offers some potential options from a multi-hazard and policy perspective as agencies work toward flood hazard mitigation solutions in the region.

The Canterbury region of New Zealand is vulnerable to a wide range of hazards including earthquakes, flooding, storms and fires (ECAN, 2014). While no single multi-hazard plan controls hazard policy making and implementation in the region, collective actions by government entities do constitute a multi-hazard perspective, especially since the CES.

From a governmental action perspective, any understanding of what is occurring in the Canterbury region resides at the confluence and outcomes of two systems: one of disaster recovery and reconstruction from the CES (as evidenced through physical infrastructure rebuilding, relocating of people and buildings; and addressing people's psychological, physical, spiritual, cultural and social needs); and the other seeking to prevent future natural hazard losses through normal functions of local government (as evidenced through regulatory adjustments and infrastructure investments). These systems are not fixed. They are adapting to the cascading influence of the CES as expressed through the floods of 2014. Therefore decisions taken in 2014 towards recovery and reconstruction are subject to continued adjustments based on the reality of the continually changing landform and governance conditions.¹

Governance agencies

There are many government entities engaged in hazards related policy work in the Canterbury region. Figure 9-1 illustrates the direct and indirect relationships among these entities that are further explained later in this section.

¹ For example: the landform conditions in 2014 are subject to continued adjustments based on altered geotechnical conditions and assessments. A storm-water solution formed today should be subject to revision as new geotechnical information arises.



Figure 9-1 Direct and indirect relationships among government entities engaged in hazards related policy in the Canterbury region

The national government (hereafter referred to as "Government") has a direct local presence through the Canterbury Earthquake Recovery Authority (CERA) formed in 2011 to direct the reconstruction phase of the recovery, and the Earthquake Commission (EQC), a crown agency formed in 1993 that insures residential property in New Zealand against natural hazards and is funding major repairs following the CES. The Government also has an indirect presence through the New Zealand Transport Agency (NZTA) that is a major funding agency for road reconstruction following the CES and an owner partner of the Stronger Christchurch Infrastructure Rebuild Team (SCIRT).

The leading regional authority is Environment Canterbury (ECAN), formed in 1989 to manage the region's air, water and land. It implements provisions of the national Resource Management Act (RMA) 1991 (New Zealand Parliament, 1991). One of ECAN's functions as a regional territorial authority is the avoidance or mitigation of natural hazards (RMA 30 (1,C, iv)).

In the metropolitan portion of the Canterbury region there are three district (municipal, locallevel) councils: Christchurch City (population 379,000 in 2010) and the districts of Waimakariri (encompassing the towns of Kaiapoi and Rangiora, population 47,600 in 2010), and Selwyn (population 39,600 in 2010) (Statistics New Zealand, 2010). New Zealand does not have states as does Australia or the United States, nor provinces, such as Canada. Thus, the actions of Government directly influence the local government authorities.

Regulatory Framework

The Resource Management Act (RMA 1991) guides environmental management of natural and physical resources, including land use development and permitting processes (New Zealand Parliament, 1991). The Local Government Act (LGA 2002) defines the authorities, responsibilities and powers conferred from Government upon local territorial authorities (New Zealand Parliament, 2002).

The Canterbury Earthquake Recovery Act (CER Act 2011) gives powers to the Government appointed Minister for Canterbury Earthquake Recovery to suspend or make exemptions to almost any New Zealand law including parts of the RMA 1991, and LGA 2002 (New Zealand Parliament, 2011). This legislation will remain in effect at least until 2016 when it is set to expire, at which time CERA would also cease operations in its present form.

ECAN has two major roles related to land use, and flooding and storm water management in the region. The first is through its water management plan. The second role arose via the Earthquake Minister's request in November 2012: in this role ECan has been the lead agency developing the region's Land Use Recovery Plan (adopted December 2013), in collaboration with the NZTA, local councils, and others. The Land Use Recovery Plan is a statutory document, prepared under the CER Act 2011. In this document the Christchurch City Council, Waimakariri and Selwyn District Councils and ECan are directed to make land use changes to district plans, the Canterbury Regional Policy Statement and other instruments in order to accommodate the region wide population growth anticipated in recovery following the CES.

ECAN also develops the region's water management strategy, but the CCC designs, manages, and maintains its own storm-water system under this strategy. The CCC has a statutory obligation under the RMA (1991) to address floodplain management. As recently as January 2011 (just prior to the damaging February 22, 2011 earthquake), the CCC had done so through Operative Variation 48 Management of Flood Hazard in Christchurch (Christchurch City Council, 2011). This specifically identified areas of the city subject to greater risk of flooding than the city generally, and imposed controls on new construction (both the land filling and floor levels for buildings) within those areas.

The District Plan for Christchurch defines the framework for land use and subdivision of land within the district. One of the most important plan chapters is Natural Hazards, where it defines the Flood Management Area (FMA) boundaries (based on Operative Variation 48) and associated regulations for granting various types of consents (permission to build). The District Plan is being updated, and when adopted, the update will have legal status and most likely greater land use controls. The Waimakariri and Selwyn District Councils have similar Natural Hazards chapters in their district plans.

Instruments: Insurance

Insurance generally is used as an instrument for businesses and individuals to transfer risk, and, in turn, to obtain funds for use following a specific type of damaging or injurious event. There are unique aspects of New Zealand's natural disaster insurance system that have a direct impact on the Canterbury earthquake recovery process and issues related to the March 2014 flooding. The Earthquake Commission (EQC) is a Crown entity, established under the Earthquake Commission Act 1993 to provide Government-backed natural disaster insurance for residential property (contents, dwellings and some coverage for land underneath dwellings), against loss or damage from earthquakes, volcanic eruptions, hydrothermal activity, tsunamis, natural disaster fires and natural landslips (New Zealand Parliament, 1993). There are payment limits on EQC coverage so that most residential property owners also obtain 'over-cap' coverage from private market insurers. As compared to most countries in the world, a large portion (80%) of the residential losses in the CES was covered by insurance (Miles et al., 2014). Private market insurers also provide commercial coverage. There is additionally a local authority protection insurance fund to help finance repairs to local public facilities and infrastructure.²

It is important to understand New Zealand's unique land insurance coverage. The Earthquake Commission (EQC) Act (1993) specifies that damage caused by the specified natural disasters will be remediated as part of the residential insurance settlement process. The EQC Act specifically covers the land upon which the residential building (and any related outbuildings) are situated; all land within 8 m of the horizontal building line; and some portions of the land underneath the primary access point to the site, such as a driveway. New Zealand may be the only place in the world that provides this coverage; as such coverage is not available in the United States, Canada, Japan, Mexico, China, and Chile to name some countries with high seismic risk. The EQC policies also provide for some limited coverage for land damage caused by storms and floods, but the policyholder must have private insurance to cover flood damage to the residential structure or contents (EQC, 2012).

Increased Flooding Vulnerability (IFV) caused by earthquakes is a type of land damage that can be covered under an EQC policy. The EQC reports that there are 309 properties currently on hold within the Canterbury Home Repair Programme (CHRP) because the property has been identified as potentially having IFV land damage from the CES (EQC, 2014). Modeling is currently underway by the EQC's geotechnical engineers, Tonkin and Taylor, and their May 2014 scheduled report will delineate the extent of flood prone properties impacted by the CES. After this, EQC will advise all affected property owners of the next steps in settling their land claim. The EQC reports that some of the properties fall within the Christchurch City Council's existing flood management areas (FMAs), while other are outside the FMA boundaries. A 2012

 $^{^2}$ In 1993, local authorities created a Local Authority Protection Programme (LAPP) fund and make annual contributions to the fund to meet their 40% share of the costs to restore essential local infrastructure (such as local roads, potable water and wastewater systems, and stop banks) after a natural disaster; New Zealand's Government contributes 60%.

CCC report states that there are 1,268 more properties with a potential to flood within the Avon Styx and Heathcote catchments since the earthquakes (CCC, 2012; 2). The EQC and CCC statements establish a range of possible earthquake associated flood damage categories for properties, but not an absolute number that experienced land damage.

SCIRT

The Stronger Christchurch Infrastructure Rebuild Team (SCIRT) is an alliance formed in 2011 to rebuild damaged street level civic infrastructure—roads, bridges and retaining walls, and potable water, wastewater, and storm water systems—in the Canterbury region damaged by the CES (SCIRT, 2014). The alliance is between three funders (CERA, NZTA and CCC) and five New Zealand construction firms (City Care, Fletcher Construction, Fulton-Hogan, McConnell Dowell and Downer). SCIRT is structured with a Board drawn from the Principals, a management and integrated services team, and five delivery teams, one each from the constructor principals. SCIRT is estimated to spend NZ\$2.5 billion before the alliance is dissolved and works are transferred back to NZTA (highways only) and into the CCC administrative structure in December 2016.

SCIRT's earthquake-related repair works that are most relevant to flood hazard management are the storm-water system repairs and repairs to roads and bridges in flood-prone areas. The Alliance Agreement created in 2011 calls for rebuilding infrastructure at least to pre-earthquake standards.³ In practice, SCIRT's policy has been to repair and rebuild the networks using a 'like for like' approach, except when there is a more modern material or method to use when needed. Under general operational rules, there are no provisions for major upgrades or improvements *per se*, but requests can be made for enhancements by owner partners or promoted by SCIRT for such as network rationalization. The CER Act (2011) does provide statutory language that can allow for this. For example, with respect to storm water management, a set of SCIRT 'network level of service' parameters (i.e. operational cost, effectiveness, resilience and remaining asset life considerations) drives the decisions on what and how to replace various system elements.

CERA

The Canterbury Earthquake Recovery Authority (CERA) is the agency established by the Government to lead and coordinate the ongoing recovery effort following the CES. CERA reports to the Minister for Canterbury Earthquake Recovery, Gerry Brownlee, who is responsible for coordinating the planning, spending, and actual rebuilding work needed for the recovery on behalf of the Government. Special powers have been vested in the Minister for Canterbury Earthquake Recovery and CERA in order to enable an effective, timely and coordinated

³ This agreement marks the transition from the Infrastructure Recovery Management Organisation (IRMO) repair works to the more comprehensive rebuilding works being undertaken by the Alliance.

rebuilding and recovery effort.⁴ CERA is an 'owner participant' partner in SCIRT, and has a voice in the reconstruction of all the horizontal infrastructure networks.

Also, since 2011, the Government, through CERA, has been implementing a buyout of over 7,300 properties in the Christchurch and Waimakariri districts. Collectively termed the "Residential Red Zone" (RRZ), these properties are located on the eastern flat lands area and in the Port Hills suburbs. Much of the RRZ area is near the Ōtākaro/Avon River, which is where water from the Dudley Creek flood area is conveyed, and other tributaries running through the flat lands of Christchurch's eastern suburbs. RRZ areas are defined as having significant and extensive area wide land damage during the CES where the success of engineering solutions may be uncertain in terms of design, and possible commencement, given the ongoing seismic activity, and any repair would be disruptive and protracted for landowners (CERA, 2014a). Given the size of the problem (the number of affected properties, the uncertainty about the cost and time required for repairs, the Government's long term exposure to liability and the on-going seismic risk), Government acquisition became an acceptable alternative strategy to displacing residents for prolonged period of time to complete the recommended area-wide land remediation works (Rogers et al. 2014).

Analysis: Gaps in the present system

Christchurch is facing, and working to address, a long-term problem: flooding (meaning exceeding the capacity of the in-place storm management system to convey water within its boundaries) that has been exacerbated by the CES. There were flood problems before the earthquakes but the land subsidence and other differential settlements caused by the earthquakes have exacerbated the flood hazard management issues in the region. The CCC is working to strengthen its regulatory framework and also considering sea level rise in updates (e.g. Variation 48), and the instruments (technical, i.e. Flood Management Areas, and legal) are understood by staff (Waste Water and District Plan update personnel) who were interviewed. The challenge now is determining the potential frequency of large rainfall or tidal events and severity (i.e. expected damage levels given the present urbanization settlement pattern) and determining what can feasibly be done, and by whom.

Based on field observations and a review of key technical studies (e.g. Tonkin and Taylor, 2013), it is posited that the problem has a series of parts, including:

- improve the conveyance capacity of the present storm water system;
- review the design parameters of current flood models to ensure that they are considering the 'new normal' for flooding impacts post-CES, especially in light of the March and April 2014 experiences;
- consider whether the proposed Flood Management Areas (FMAs) in the draft natural hazards chapter of Christchurch's District Plan are large enough to address future flood risk;

⁴ CERA closely coordinates its efforts with the Ministry of Social Development and Housing New Zealand. These agencies do not provide direct hazard related services, and therefore are not included in this section's analysis.

- determine who pays for any proposed changes to infrastructure (i.e. storm water system) or other flood management strategies;
- determine how improvements get made, that is, who does the work of design and construction; and
- determine what policy steps are needed to reach good outcomes.

Possible options to consider

The Canterbury region faces new flood hazard conditions caused by the altered landform of the Canterbury Earthquake Series (CES). If not addressed now, flooding hazards and risks will be magnified, in a continuation of bad outcomes. The organizational framework for an immediate "betterment" approach to storm water is in place in the Canterbury region, benefited in part by the infusion of regulatory (CER Act 2011 Variation 48, CERA Land Use Recovery Plan), technical (major private sector geo-science support), and financial resources (e.g. \$NZ 2.5 billion for SCIRT) following the CES.

Based upon this review, six policy options are offered to address the increased flood vulnerability caused by the CES, as well as providing some added long-term benefits to help address the anticipated effects of climate change (i.e. precipitation and sea level rise) and future land use patterns. The first four are more reflective of the status quo and the district councils' traditional lead responsibilities in flood hazard management. The other two look more collaboratively to leverage the resources of governmental arrangements currently working in the region, particularly the CCC (and other district councils depending upon scope), CERA, and the EQC. By collectively pooling and leveraging of resources (particularly RRZ land, EQC claims obligations, and on-going flood and earthquake related works of the CCC and SCIRT), both the current flooding problems and any future flood liabilities caused by known gaps in the region's storm water management system may be more substantially reduced, and in a much more timely and effective way.

1. <u>Improve the overall maintenance and repair of the current system to assure maximum conveyance of the existing system</u>. This might include reducing obstructions such as residential bridges over drainage ways. The responsibility of this task lies mainly with the CCC and other district councils.

2. <u>Undertake more locally focused incremental improvements</u>. In March 2014, the Christchurch City Council received an engineering report (Jacobs, 2014) that offered two options for addressing post-earthquake flooding in the Flockton area of the Dudley Creek catchment. Option 1 proposed channel and culvert upgrades that are projected to protect 550 properties at a cost of NZ \$50 million. Option 2 proposes a pump station and channel upgrades that are projected to protect 490 properties at a cost of NZ\$ 53 million. Option 1 requires channel widening within the Residential Red Zone, while Option 2 does not. Thus, Option 1 may require easements and conditions of use granted by the Government and other affected property owners. These options are based upon projected 50-year annualized rainfall probability estimates and would provide a partial solution to some of the more pressing flood hazards (like the recent

March and April 2014 flood events). The designs would not, however, address the flood risks associated with more extreme events. The Ōpāwaho/Heathcote River area floods near the estuary entrance are not considered in the scope of the aforementioned proposals but will shortly be addressed via a separate series of proposed solutions. Both of the Dudley Creek options would also take an estimated two years to implement. These are considered to be more near-term and focused actions, similar to the incremental policy taken by the Drainage Board that became part of the CCC in 1989 (CCC, 1989).

<u>3. Develop an updated storm management plan for the Ōpāwaho/Heathcote River</u>. Properties in the river basin have experienced repeated flooding in March and April 2014. Studies similar to those undertaken for the Dudley basin are underway for the Ōpāwaho/Heathcote River areas.

4. <u>Expand the flood management areas</u>. In 2011 the CCC amended the District Plan through Operative Variation 48.⁵ This document forms the basis for the updated *Natural Hazards Chapter* of the District Plan which is currently in development and in which Christchurch is proposing a 30% increase in the size of the FMAs. This update will provide the CCC with more consent (building permission) control in high hazard areas and also ensures disclosure of flood exposure through the Land Information Memorandum (LIM) process.⁶ This potential policy consideration would help ensure that any new development (or significant redevelopment of existing buildings) incorporates flood mitigation measures.

5. <u>Incorporate regional storm water management into the planning for the future use of the RRZ</u>. The RRZ may be a key asset for regional flood hazard management. The RRZ can be used to increase conveyance and detention capacity, particularly for water collected north of the $\bar{O}t\bar{a}karo/Avon$ River in Christchurch; and similar opportunities may exist for Red Zone lands in Waimakariri District as well. Enhanced storm water options may provide long-term benefit for the region's economy and a substantial multi-hazard risk reduction solution for its residents.

CERA recently announced that planning for the future use of RRZ would commence in 2014 (CERA, 2014b). RRZ planning might consider which areas are most appropriate for stormwater detention and conveyance and, as such, what easements and conditions of use (e.g. how much water, and for how long detained) are needed, and how conveyance would be managed into the estuary or other outlet. Prior to establishing the Residential Red Zone, the CCC had adequate authority through the Christchurch District Drainage Act (1969) to acquire and utilize lands within its geographic limits for conveyance. Once purchased, the RRZ lands become Government property, and an agreement for easement and use, and acceptable payment program,

⁵ See http://resources.ccc.govt.nz/files/Variation48-OperativeDocument.pdf

⁶ A LIM contains all the information that the Council holds on a property including: special characteristics of the land or buildings any current requisitions issued by the Council on the property, drainage information relating to sewer and/or storm water, and resource consents issued in the immediate neighborhood (default radius of 100m). (http://www.ccc.govt.nz/homeliving/goaheadbuildingplanningS00/propertyinformation-s09/limcontent-s09-02.aspx).

the scoping of necessary works may need to involve the CCC (and Waimakariri District, depending upon the scope), ECAN, SCIRT, EQC, CERA, the Government and other property owners as necessary.

6. Develop and implement collective agreements on an expanded scope of work for storm water improvements made as part of the earthquake recovery. In areas where earthquake land alterations have changed the runoff and flow characteristics (i.e. higher water table levels) and thus exacerbated flood risk, collective agreements on enhanced storm water conveyance improvements (to a pre-determined flood (storm) risk management level) may help reduce the recurring flood impacts in some neighbourhoods for small to medium size events. Special improvement areas could be designated to manage the upgrading on an on-going basis. The working party might involve the CCC (and Waimakariri District, depending upon the scope), ECAN, SCIRT, EQC, and CERA. Such a solution might also involve some alterations on private property. It should be noted that it is also unlikely to prevent the effects of large (low return interval) future events and can only be sustainably implemented where sea level rise effects will not cause gravity drainage problems.

SCIRT might be engaged to perform some of the necessary work. However, SCIRT's current scope of work and budget are based on a policy directive of replacing earthquake damage with "like-for-like" solutions. Recent flooding in March and April 2014 suggest that the like-for-like approach to returning to pre-earthquake conditions may not be sufficient to manage the new stormwater management issues resulting from the CES. SCIRT has the engineering capacity as well as the delivery capacity to execute projects as directed by the owner partners. As an owner-participant in SCIRT, the Christchurch City Council (CCC) might make the case for increased storm-water protection. Also, the CER Act defines recovery as including "restoration and enhancement" (CERA, 2011) and, thus, may provide the necessary statutory language for CERA to support SCIRT in designing and implementing enhancements to the storm drainage system as part of its earthquake-related repair and rebuilding work.

Any scope changes would likely require an adjustment in the SCIRT delivery schedule and the overall budget. To help finance this work, the owner partners might be able to use EQC funds for the neighborhood-level costs related to improve local conveyance and reduce potential stormwater impacts on EQC land damaged insured properties. EQC funding for properties with earthquake identified land impacts might be directed to help offset costs for the necessary neighbourhood flood improvements. EQC has been working to identify properties potentially affected by IFV using topographical information and modeling of the river flow and overland flow (effects of rainfall) for the Pūrākaunui/Styx, Ōtākaro/Avon and Ōpāwaho/Heathcote Rivers. Information from these studies will establish a basis for choosing schemes for the EQC contribution to the problem solution. These works could complement more regional stormwater management efforts that might address conveyance and storage along the Ōtākaro/Avon River, Ōpāwaho/Heathcote River and other major tributaries.

The problem at hand requires a policy directive that drives the engineering solution. This starts by accepting the 'new conditions' in the region (Alesch and Siembieda 2012), and, through a broad based sense of necessity, closes the present water management network gaps. The CERA Recovery Strategy for Greater Christchurch (Section 2) speaks to "working together, taking an integrated approach, and looking to the future" (2012). This is an adequate basis for a multi-stake holder conversation to take place.

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