The Effect of Sea Level Rise on Liquefaction Vulnerability

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ABSTRACT

The 2010-2011 Canterbury Earthquake Sequence (CES) caused widespread liquefaction related damage. The extent and severity was primarily influenced by the level of earthquake shaking, soil conditions and depth to groundwater. The CES also caused ground surface subsidence and as a result the ground surface is now closer to the groundwater level, causing the land to become more vulnerable to liquefaction damage in future earthquake events. Sea Level Rise (SLR) will raise groundwater levels in low lying coastal areas. Using the Canterbury geotechnical dataset, the increases in liquefaction vulnerability from SLR are examined and the implications for future land use planning and development of low lying coastal areas with liquefaction susceptible soils is discussed. Appropriate consideration of the increased liquefaction vulnerability due to SLR will introduce a challenging balance for investors, regulators and the public, between commercially and aesthetically attractive coastal expansion, and more resilient long-term development that accounts for hazards associated with climate change.

Introduction

The Canterbury Earthquake Sequence (CES) caused both widespread liquefaction related land damage (shown in Figure 1b) and building damage. It has had an enormous social and economic impact on Christchurch and New Zealand. Liquefaction related damage affected 51,000 of the 140,000 residential properties in Christchurch and caused approximately 15,000 residential houses to be damaged beyond economic repair as a direct result of liquefaction related land damage. The severity of the damage was primarily influenced by the levels of earthquake shaking (i.e. magnitude and peak ground accelerations), subsurface soil conditions and depth to the groundwater surface. Topography, proximity to rivers and streams and land use also influenced the distribution of liquefaction related land damage. The CES caused regional tectonic subsidence as well as widespread liquefaction related subsidence. In Christchurch 85% of the urban residential flat land properties have subsided (both tectonic and liquefaction related). This has left a legacy of a city with suburbs that are now more flood prone (Hughes et al., 2015 and Jackson et al., 2015) and more vulnerable to liquefaction damage in future earthquake events because the ground surface is now closer to the groundwater level (Russell et al., 2015). Some Christchurch suburbs have experienced changes in relative groundwater levels equivalent to a century (0.5 to 1 m) of Sea Level Rise (SLR) as a result of the CES. The observed effects of the subsidence provide insight into the potential impacts of SLR in other coastal areas throughout the world both in terms of flooding and liquefaction vulnerability (Russell et al., 2015).

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This paper considers the potential effect of SLR on liquefaction vulnerability in low lying coastal environments using the 15,000 Cone Penetration Tests (CPT) dataset in Christchurch, available from the Canterbury Geotechnical Database (CGD)[4]. The changes in liquefaction vulnerability as a result of future rises in sea level of 0.5 and 1 m are considered (not the changes of relative SLR due to the subsidence caused by the CES). This paper is divided into three parts, starting with the development of future groundwater surfaces for the two SLR cases, then using the two SLR groundwater scenarios, coupled with the geotechnical dataset, to assess the changes in potential liquefaction vulnerability as a result of higher groundwater levels and then considering the implications for land use planning and development. A model of the existing Christchurch median groundwater surface (presented in van Ballegooy et al., 2014a) was modified to reflect possible changes in the groundwater for the two SLR scenarios. The modified groundwater surfaces for each scenario are based on simplified assumptions. While the validity of these assumptions can be debated, the primary objective of this paper is not to determine in detail how groundwater will respond to SLR in Christchurch, but to generically demonstrate the potential effect that rising sea levels will have on liquefaction vulnerability of low lying coastal environments.

Development of Modified Groundwater Surfaces for Various Sea Level Rise Scenarios

One-dimensional steady state backwater profile modelling of the Waimakariri, Styx, Heathcote and Avon rivers (shown in Figure 1a) based on the median river flow rates was done using the software HEC RAS, US Army Corps of Engineers (2010), to better understand how SLR could affect river backwater profiles. An example of a backwater profile based on the median flow rate for the Avon River is shown by the solid black line in Figure 1c. This shows the median water level of the river rising from right to left with increasing chainage upstream along the center-line of the river. No direct modelling of the hydraulic effect or changes in the shape of river cross-sections, direction of flow, or other two and three dimensional aspects of flow were undertaken as part of the HEC RAS backwater profile modelling. A Mannings (roughness) coefficient (n) of 0.03 for a clean natural channel was assumed as a constant for all four rivers. Notwithstanding the simplified assumptions, general consistency was observed between the NIWA river gauge station data (NIWA, December 2014) and the modelled HEC RAS backwater profiles.

The sea level at existing coastal margin for each river was elevated by 0.5 and 1 m and new backwater profiles were generated (Figure 1c). The backwater profiles representing the existing median level were subtracted from each SLR backwater profile to establish potential additive groundwater values in 250 mm increments along the chainage of each river for each SLR scenario. The maximum inland extent where the SLR affects the river backwater profiles for the 0.5 and 1 m SLR cases are shown as points A and B respectively for each river on Figure 1a. These points generally occur at the same distance in from the coast, which means that increases in groundwater levels due to SLR are generally confined to the land east of Fitzgerald Avenue which is on the eastern side of the Central Business District (CBD). The additive groundwater values in 250 mm increments along the chainage of each river for each SLR scenario were contoured and are shown as black lines on the maps in Figures 1d and 1e. The additive SLR groundwater contours for each scenario have been applied to the existing median groundwater surface (van Ballegooy et al., 2014a) based on the following simplifying assumptions; 1) river

[4]Available from https://canterburygeotechnicaldatabase.projectorbit.com as at June 2014.

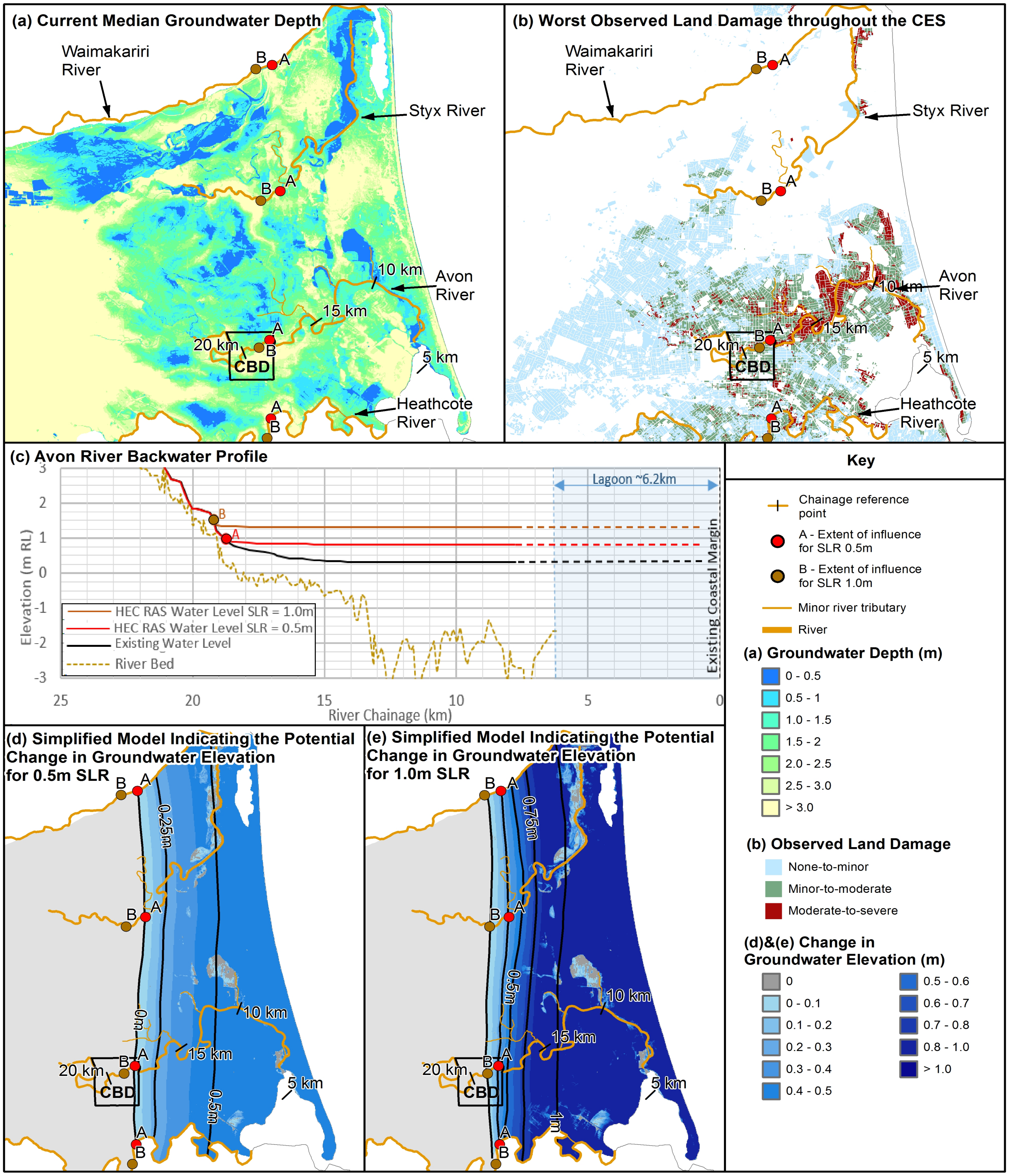

Figure 1: (a) Existing median depth to the groundwater surface (reproduced from van Ballegooy et al., 2014a). (b) Observed liquefaction related land damage as a result of the CES (reproduced from van Ballegooy et al., 2014b). (c) Avon River backwater profile modelled using HEC RAS. (d & e) Simplified model of the potential change in groundwater elevation for 0.5 and 1 m SLR.

levels and surrounding shallow groundwater profiles are perfectly hydraulically linked with one another. This simplification means that rises in backwater profiles will result in similar rises in surrounding groundwater levels; and; 2) no anthropogenic changes will occur to the river levels and groundwater levels.

In reality, as sea levels rise, coastal defenses such tide gates and stopbanks might be built in the future to stop the land from being inundated and also groundwater drainage works might be undertaken. This is because it is difficult to know how much anthropogenic intervention will occur. In their 2014 report, the Intergovernmental Panel on Climate Change (IPCC) refer to atmospheric warming and composition change which is likely to result in changes to rainfall and snow melt. No allowance for these additional climatic changes are included in the simplified model of the potential change in the groundwater surfaces (Figures 1d and 1e). Likewise, the effects of minor river tributaries (shown in Figure 1) have not been included in the HEC RAS modelling. The time taken for the freshwater-saltwater transition zone to reach equilibrium with SLR can vary significantly. However, the highly permeable ground in Christchurch has been shown to have a quick response time and steady state equilibrium can be reached relatively quickly. Storm events and seasonal rainfall patterns cause fluctuation of the groundwater surface (van Ballegooy et al., 2014a) by a similar amount as the SLR being considered in this study. It is noted that there are some areas in eastern Christchurch where the existing median groundwater surface is already close to the ground surface and therefore the potential rises in groundwater are limited (i.e. once the groundwater rises above the ground surface there is no further decrease in the depth to groundwater). These areas can be seen on the maps in Figures 1d and 1e.

Changes in Liquefaction Vulnerability for Various Sea Level Rise Scenarios

Liquefaction vulnerability evaluations in the Christchurch area have made extensive use of four Cone Penetration Test (CPT)-based liquefaction vulnerability parameters (or indices) including; one-dimensional (1D) post-liquefaction reconsolidation settlement (S_{V1D}), liquefaction potential index (LPI), modified liquefaction potential index (LPI_{ISH}) and liquefaction severity number (LSN). These liquefaction vulnerability parameters all use a liquefaction triggering analysis as one step in their calculation. The ability of the S_{V1D}, LPI, and LSN parameters, in combination with some common liquefaction triggering correlations, to reasonably predict the observed liquefaction-induced damage on a regional scale was evaluated by van Ballegooy et al. (2014b, 2015a and 2015b). Their conclusions included: (1) the Boulanger and Idriss (2014) liquefaction triggering procedure produced slightly better correlations with observed liquefaction-induced damage for each liquefaction vulnerability parameter compared with the other commonly used methods, (2) the LSN liquefaction vulnerability parameter provided a more consistent correlation with the observed liquefaction related damage compared with the other liquefaction vulnerability parameters, and (3) use of liquefaction vulnerability parameters in regional studies can, at best, only provide general assessments of liquefaction-induced damage patterns. Observed liquefaction related land damage during the CES (Figure 1b) generally correlate with the following LSN ranges: 0 to 15 generally correlates with none-to-minor liquefaction related land damage, 16 to 25 generally correlates with minor-to-moderate liquefaction related land damage and more than 26 generally correlates with moderate-to-severe liquefaction land damage.

For this study the LSN liquefaction vulnerability parameter was used to assess the potential changes of liquefaction vulnerability in susceptible soils in low lying coastal environments. The changes to the liquefaction vulnerability have been assessed at the Serviceability Limit State (SLS), Intermediate Limit State (ILS), and Ultimate Limit State (ULS) design cases (representing the 25, 100 and 500 year return period levels of earthquake shaking in Christchurch). The Magnitude (M) and Peak Ground Acceleration (PGA) values for the SLS, ILS and ULS design cases are specified in the MBIE (2012 & 2014) guidelines, for the SLS and ILS cases the design PGA values are 0.19g and 0.30g for a M6 earthquake and for ULS are 0.35g for a M7.5 earthquake. Studies undertaken by van Ballegooy et al. (2015b) show that the ULS M7.5 0.35g ground motions results in virtually the same LSN values in Christchurch compared to the equivalent M6 0.52g ground motions, when using the Boulanger and Idriss (2014) liquefaction triggering assessment methodology. Therefore, for simplicity, the ULS case has been modelled using the M6 0.52g ground motions. For each of the SLR cases the LSN parameter was computed at each CPT location using the respective groundwater surfaces based only on the top 10 m of any CPT sounding (as discussed in van Ballegooy et al., 2015b). In order to apply the four methods to a regional study of 15,000 CPT (available from the CGD), assumptions have been made including:

- The probability of liquefaction triggering curves adopted are the 15 percentile curves;
- No liquefaction occurs where the soil behaviour type index, $I_c > 2.6$; and
- The soil Fines Content (FC) was estimated in accordance with the Boulanger and Idriss (2014) method-specific FC-I_c correlation assuming a default C_{FC} fitting parameter of zero.

The calculated LSN values at each CPT location have been interpolated between CPT investigation locations (based on a natural neighbour method which calculates Thiessen polygons and weights them with proximity to CPT locations). Figure 2 shows coloured contour plots of the liquefaction vulnerability (LSN) maps for the current median groundwater surface case and the 0.5 and 1 m SLR cases (rows 1, 2 and 4 respectively) at the SLS, ILS and ULS levels of earthquake shaking (columns 1, 2 and 3 respectively). Difference maps showing the increase in liquefaction vulnerability as a result of 0.5 and 1 m SLR are shown in rows 3 and 5 respectively. The maps indicate substantial increases in LSN (and consequently liquefaction vulnerability) are likely to occur in eastern Christchurch where the greatest increases in groundwater levels are expected. The increases in LSN resulting from 0.5 m SLR are generally localised in effect, but at 1 m SLR the increases in LSN are more continuous and widespread. As noted earlier, in the localised areas where the groundwater is already close to the ground surface, the increase in LSN is much smaller. Also, in parts of eastern Christchurch the LSN increases less than other parts as a result of differences in the soil density and soil type (i.e. areas with silty soils or dense soils near the ground surface have smaller increases in LSN compared to areas with loose to medium dense sandy soils).

The coloured histograms in row 6 of Figure 2 provide a relative measure of the proportion of residential properties in eastern Christchurch (i.e. east of Fitzgerald Avenue) likely to experience: none-to-minor liquefaction related land damage (denoted by the blue portions of the histograms), minor-to-moderate liquefaction related land damage (denoted by the blue portions of the histograms) and moderate-to-severe liquefaction related land damage (denoted by the red portions of the histograms) for the various SLR and earthquake shaking scenarios. These

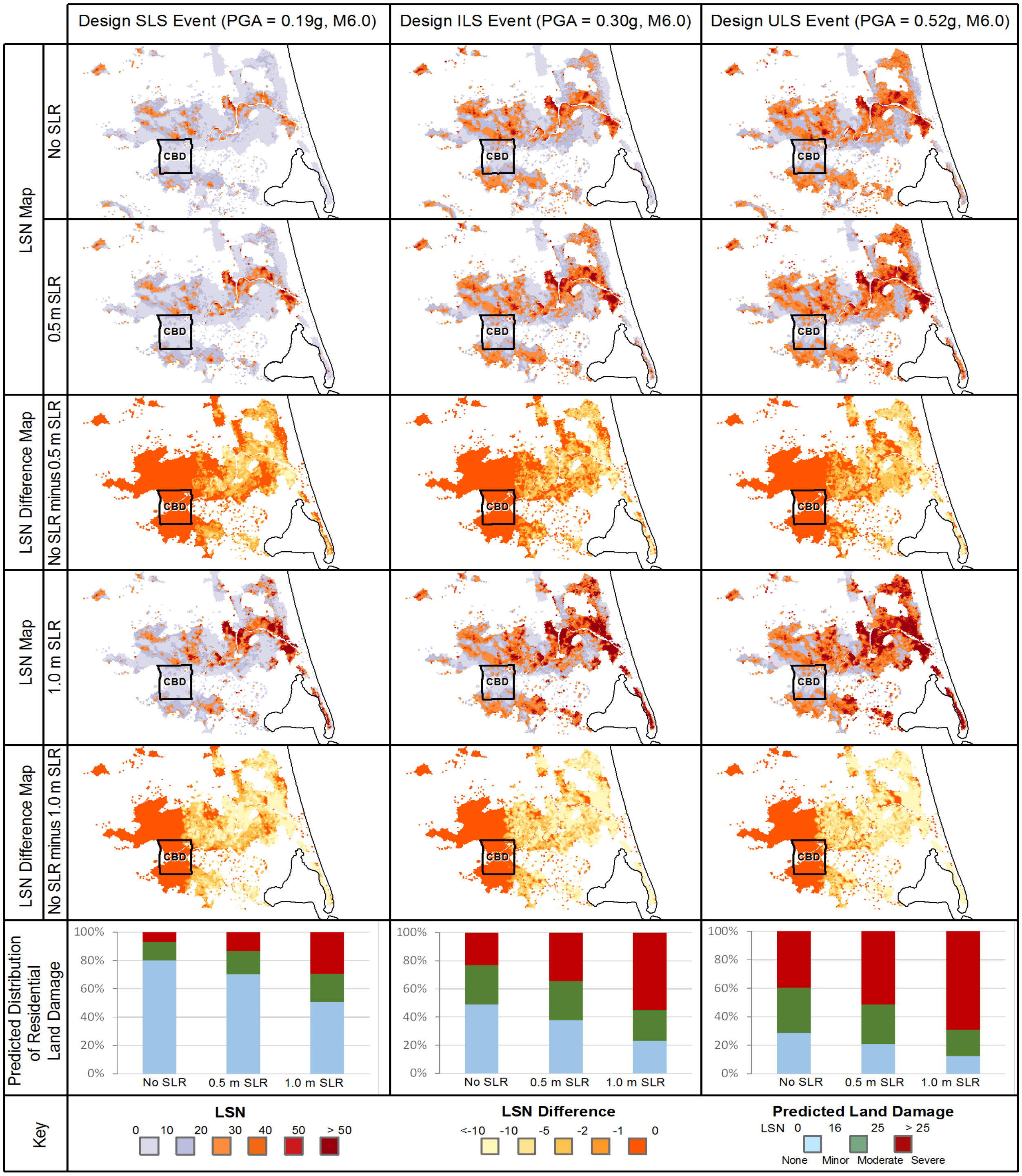

Figure 2: Spatial distribution of LSN based on the existing median groundwater surface and the groundwater surface after 0.5 and 1 m SLR (rows 1, 2, 4 respectively) for the SLS, ILS and ULS earthquake scenarios (columns 1, 2 and 3 respectively). Difference maps showing the increase in calculated LSN for 0.5 and 1 m SLR are shown in rows 3 and 5 and modelled distributions of expected land damage for the various SLR and earthquake shaking scenarios for the existing pre-CES urban residential property portfolio in eastern Christchurch are shown in row 6.

analyses indicates that SLR is likely to significantly increase in the proportion of residential properties in eastern Christchurch with expected moderate-to-severe liquefaction related land damage for the various levels of earthquake shaking. The increase in the proportion of properties expected to have moderate-to-severe liquefaction manifestation increases approximately in the order of 2 and 4 times for the 0.5 and 1 m SLR cases respectively at the SLS and ILS levels of earthquake shaking and 2 and 3 times for the 0.5 and 1 m SLR cases respectively at the ULS levels of earthquake shaking. Where groundwater levels are less than 1 m below the ground surface, the LSN parameter becomes sensitive to adjustments in groundwater. Sensitivity analyses have therefore been undertaken by only including the top 1 to 10 m of the CPT profile in order to assess the change in the LSN as a result of SLR (i.e. excluding the top 1 m of the CPT profile from the analysis). The results of the sensitivity analyses showed minimal change in the trends shown in Figure 2.

Implications for Sustainable Development and Planning

This research presents new information that is relevant for sustainable development and planning for natural hazards internationally. Planners considering natural hazards have been grappling with how to manage the potential effects of climate change and SLR. To date, their focus has been on the direct effects of these long-term, global-scale changes, and the implications for existing coastal hazards, such as flooding and coastal erosion. The potential cumulative effects of SLR and liquefaction consequences of seismic hazards has not been considered. This research shows that these cumulative effects can be significant. In New Zealand, managing these cumulative effects of natural hazards is within the remit of the Resource Management Act (RMA) as illustrated from the provisions below (emphasis added):

- The RMA's sustainable management purpose is "managing the use, development, and protection of natural and physical resources in a way, or at a rate, <u>which enables people and communities to provide for their social, economic, and cultural well-being and for their health and safety</u> while:

  (a) <u>Sustaining the potential of natural and physical resources</u> (excluding minerals) <u>to meet the reasonably foreseeable needs of future generations</u>;

  (b) Safeguarding the life-supporting capacity of air, water and soil, and ecosystems; and

  (c) Avoiding, remedying or mitigating any adverse effects of activities on the environment."

- The term effect includes (amongst other matters) "<u>future effect</u> … any <u>cumulative effect which arises over time or in combination with other effects</u>…any <u>potential effect of low probability which has high potential impact</u>".

- Natural hazards are defined as "any atmospheric or earth or water related occurrence (including <u>earthquake</u>, tsunami, erosion, volcanic and geothermal activity, landslip, <u>subsidence</u>, wind, drought, fire or flooding) the <u>action of which adversely affects to may adversely affect human life, property, or other aspects of the environment</u>.

The RMA provides limited guidance about the timeframe that should be addressed in plans and policy instruments that are prepared under the RMA. However, one national-level instrument, the New Zealand Coastal Policy Statement 2010 (NZCPS), provides a strong direction. It requires that coastal hazard risks over “at least 100 years” need to be identified assessed and considered in plans and in development control decisions. The need to think long-term is also important given that subdivision consents, and many land use consents for use and development which are granted under the RMA have no expiry date. The two SLR scenarios considered in this research are likely to occur within the timeframe of at least 100 years set in the NZCPS. The CES and this research show that liquefaction damage can occur in the more frequent SLS and ILS earthquake shaking levels and it is likely to become worse as a result of SLR. Accordingly, the cumulative effects of the interaction of SLR with earthquake induced liquefaction should be considered as regional and district-level RMA policies and plans are prepared and reviewed throughout the country, and as applications for resource consents are determined.

The reality of a potential for significant cumulative effects from SLR and earthquake events within a 100-year timeframe emphasises the need for planners and other stakeholders to consider interactions between natural hazards. Planners and other stakeholders need to focus their attention and work together to develop appropriate and effective planning and development controls to manage the cumulative effects to deliver resilient and sustainable urban development.

Acknowledgments

This work was made possible by site investigation data have been provided courtesy of the NZ Earthquake Commission and Canterbury Earthquake Recovery Authority accessed through the CGD. The authors would also wish to acknowledge Cesar Lador, Chris Thurlow, Tony Reynolds and Virginie Lacrosse from Tonkin & Taylor Ltd who have all contributed towards the analyses presented in this paper.

References

Boulanger, R. W., & Idriss, I. M. (2014). *CPT and SPT based liquefaction triggering procedures.* Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA. Report No. UCD/CGM-14/01.

Hughes, M., Quigley, M., van Ballegooy, S., Deam, B., Bradley, B., Hart, D., & Measures, R. (2015, March/April). The sinking city: Earthquakes increase flood hazard in Christchurch, New Zealand. *GSA Today,* ***25***(3), pp. 4-10. doi:10.1130/GSATG221A.1

IPCC. (2014). *Climate Change 2014 Synthesis Report, Summary for Policymakers.* Intergovernment Panel on Climate Change. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_SPMcorr2.pdf

Jackson, M., Taylor, M., Ng, K., & Fisher, T. (2015). Increased flooding vulnerability - A new recognised type of land damage. *Proceedings of the 12th Australia New Zealand Conference on Geomechanics* (pp. 1123-1130). Wellington, New Zealand: NZGS & AGS.

MBIE. (2012). *Repairing and rebuilding houses affected by the Canterbury earthquakes.* Ministry of Business, Innovation and Employment. December 2012.

MBIE. (2014). Clarifications and updates to the Guidance 'Repairing and rebuilding houses affected by the Canterbury earthquakes' Issue 7. Christchurch, New Zealand: Ministry of Business, Innovation and Employment. October 2014. Retrieved from http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/residential-guidance-clarifications-issue-7.pdf

New Zealand Government. (2010). *New Zealand Coastal Policy Statement (NZCPS) 2010.*

NIWA. (2014, December). Neon measurement web system. Retrieved from http://neon.niwa.co.nz/neon-network.aspx

Parliamentary Counsel Office. (1991). *Resource Management Act.* New Zealand. Retrieved from http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html

Russell, J., van Ballegooy, S., Rogers, N., Lacrosse, V., & Jacka, M. (2015). The effect of subsidence on liquefaction vulnerability following the 2010-2011 Canterbury Earthquake Sequence. *Proceedings of the 12th Australia New Zealand Conference on Geomechanics* (pp. 610-617). Wellington, New Zealand: NZGS & AGS.

US Army Corps of Engineering. (2010). HEC RAS. V4.1.0.

van Ballegooy, S., Cox, S. C., Thurlow, C., Rutter, H. K., Reynolds, T., Harrington, G., & Smith, T. (2014a). *Median water elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake, Version 2.* GNS Science Report 2014/18.

van Ballegooy, S., Lacrosse, V., Simpson, J., & Malan, P. (2015a). Comparison of CPT -based simplified liquefaction assessment methodologies based on Canterbury Geotechnical Dataset. *Proceedings of the 12th Australia New Zealand Conference on Geomechanics* (pp. 618-625). Wellington, New Zealand: NZGS & AGS.

van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M., Cubrinovski, M., Bray, J. D., . . . Cowan, H. (2014b). Assessment of liquefaction-induced land damage for residential Christchurch. *Earthquake Spectra,* February 2014, **30** (1), 31-55. doi:10.1193/031813EQS070M

van Ballegooy, S., Wentz, F., & Boulanger, R. W. (2015b). Evaluation of a CPT-based liquefaction procedure at regional scale. *Soil Dynamics and Earthquake Engineering, Special Issue: Liquefaction in New Zealand and Japan (In review)*.