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Estimating Co-Seismic Subsidence in the Hutt Valley Resulting from Rupture of the Wellington Fault, New Zealand

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ABSTRACT

Ground deformation can contribute significantly to losses in major earthquakes. The lower Hutt Valley of the Wellington region is adjacent to the active Wellington Fault. The long-term signal of vertical deformation there is subsidence, and the most likely driver of this is rupture of the Wellington Fault. Recent refinement of rupture parameters for the Wellington Fault, and other faults in the region, has allowed reassessment of estimates of vertical deformation in the Hutt Valley resulting from rupture of the Wellington Fault. For an "average" Wellington Fault event, we estimate subsidence of ~1.9 m near Petone, ~1.7 m near Ewen Bridge, ~1.4 m near Seaview, and ~0 m in the Taita area. Such vertical deformation would result in large areas of Alicetown-Petone and Moera-Seaview subsiding below sea level.

Introduction

The area of the lower Hutt Valley between Avalon and Petone is one of low relief, situated on an alluvial plain near the coastal fringe at the northeast edge of Wellington Harbour (Fig. 1). It is part of a sedimentary basin that includes geologically young, relatively soft sediment deposited at the mouth of the valley. The active Wellington Fault borders the northwest side of the Hutt Valley basin, and also extends along the northwest side of Wellington Harbour farther to the south.

The M_w ~8.2 Wairarapa earthquake of 1855 on the Wairarapa Fault caused 1.2-1.5 m of uplift in the lower Hutt Valley (e.g. Grapes & Downes 1997). However, the cumulative long-term vertical deformation in the valley over the last 100s of thousands of years is known to be subsidence (e.g. Begg & Mazengarb 1996; Begg et al. 2002, 2004) based on evidence from geomorphology and drillhole data from the Hutt Valley, and seismic data from Wellington Harbour. Therefore, there must be another source of vertical deformation that overwhelms the regional uplift produced by slip on the Wairarapa Fault. The most likely candidate for this subsidence is the Wellington Fault. Seismic surveys of Wellington Harbour reveal a stratigraphy that has been tilted westward towards the Wellington Fault, implying that the harbour is a half-graben (Wood & Davy 1992). Furthermore, the sediments in the harbour are increasingly deformed in proximity to the fault, implying that the Wellington Fault is a key driver of basin subsidence.

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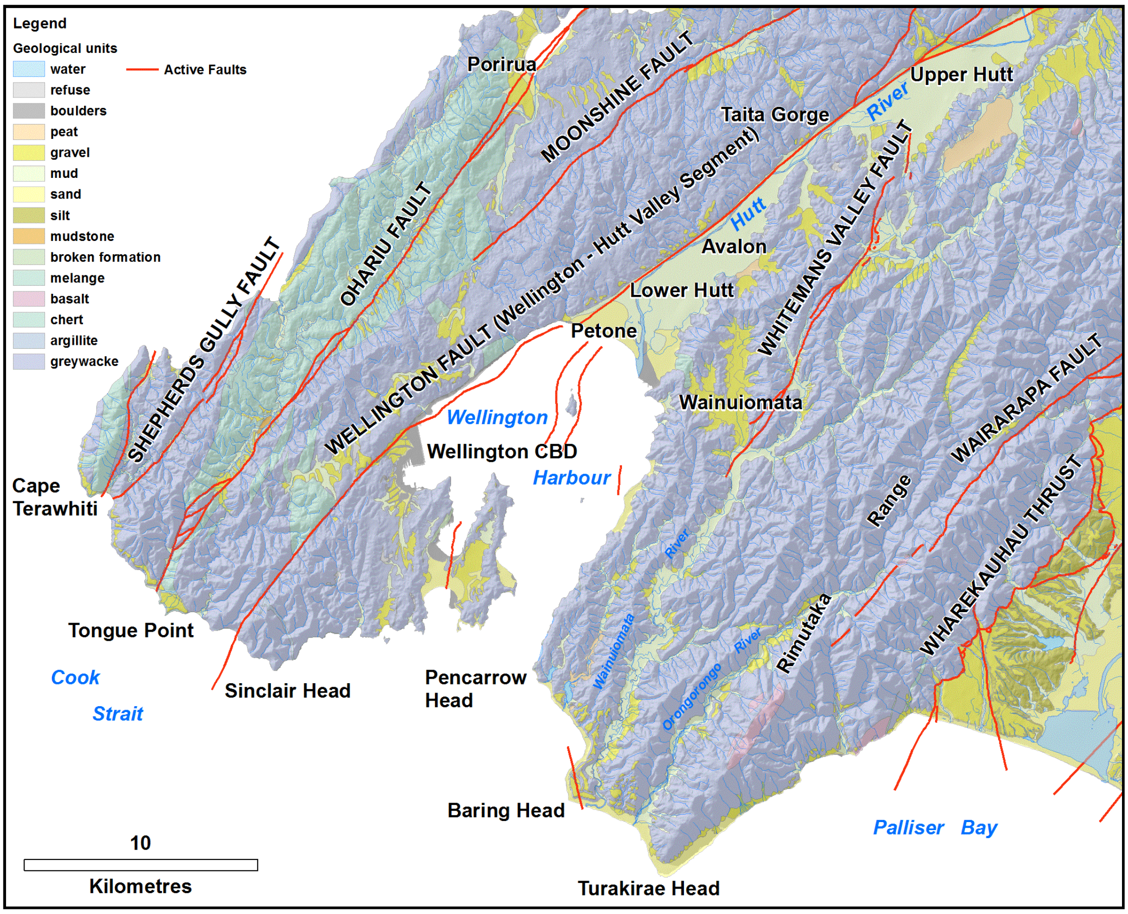

Figure 1. Location of the lower Hutt Valley in the Wellington Region, with active faults from GNS Active Fault Database (http://data.gns.cri.nz/af/) shown in red. Digital geology base layer from Begg & Mazengarb (1996).

Ground deformation can contribute significantly to losses in major earthquakes. Areas that suffer permanent ground deformation in addition to strong ground shaking typically sustain greater levels of damage and loss than areas suffering strong ground-shaking alone. The damage caused by the Christchurch earthquakes is a timely reminder that many of our towns and cities are located in areas that could sustain permanent ground deformation during seismic events. One of the recommendations of the Canterbury Earthquakes Royal Commission (Canterbury Earthquakes Royal Commission 2012) was for local and regional authorities to work to recognise areas of high potential hazard and mitigate these problems. Importantly, for low-lying urban areas near active faults, such as Lower Hutt, the 22 February, 2011 M_w 6.3 Christchurch earthquake highlighted the potential for earthquake-induced subsidence and flooding to adversely impact the urban environment.

A method for calculating co-seismic subsidence in the lower Hutt Valley as a result of Wellington Fault rupture was put-forward by Begg et al. (2002, 2004). Two of the key parameters in those calculations were the earthquake recurrence intervals of the Wellington and Wairarapa faults. The recent It's Our Fault project (e.g. Van Dissen et al. 2010) has yielded new estimates of these parameters; thus a re-appraisal of Wellington Fault-driven co-seismic subsidence is warranted. This paper presents results of a re-evaluation of subsidence hazard in the lower Hutt Valley posed by a future rupture of the Wellington Fault (Townsend et al. 2015). Incorporation of updated data for the Wellington and Wairarapa faults, along with careful quantification of associated uncertainties by employing a logic tree structure (e.g. Kulkarni et al. 1984) has allowed for a robust estimation of credible mean, minimum and maximum values for Wellington Fault-driven co-seismic subsidence in the lower Hutt Valley. Recently acquired LiDAR digital terrain data (2013) is used in association with the calculated co-seismic subsidence values to identify the areas that would be most affected by such subsidence (e.g. those areas that would subside below current sea level).

Potential societal and land-use planning implication that this subsidence may pose to Lower Hutt are outlined along with a range of possible options for managing and mitigating the hazard.

Vertical Deformation in the Hutt Valley

Subsidence rates for the lower Hutt Valley, based on drillhole data that span the last several hundred thousand years, are given in Townsend et al. (2015). Their analysis indicates that the total subsidence rate is ~0.7-0.9 mm/yr near Petone, ~0.6-0.8 mm/yr near Wakefield St, ~0.6-0.7 mm/yr at Ewen Bridge and in the central part of the valley near Marsden St, and ~0.3-0.5 mm/yr in the eastern side of the valley near Seaview. All of these cumulative subsidence values include a component of uplift contributed by slip on the Wairarapa Fault, which must be factored-in before co-seismic subsidence associated with Wellington Fault rupture can be estimated.

Long-term vertical deformation in the Hutt Valley is a combination of subsidence attributable to movement on the Wellington Fault, the uplift resulting from rupture of the Wairarapa Fault and vertical deformation that may, or may not, result from “other” factors. The relationship is given by equation (1).

$$\mathrm{Subs}_{HV} = \mathrm{Subs}_{WrF} + \mathrm{Subs}_{WgF} + \mathrm{Other} \qquad (1)$$

where Subs_{HV} is the subsidence rate calculated from the Hutt Valley drillholes.

Subs_{WrF} is the subsidence (or uplift) rate attributable to movement on the Wairarapa Fault. To derive this component of equation (1), we use the age and elevation of beach ridges at Turakirae Head to assess slip characteristics such as recurrence interval (RI) and single event vertical displacement (SEVD) on the Wairarapa Fault. Turakirae beach ridges record evidence of pre-historic earthquakes (at least four in the last ~8,000 years; McSaveney et al. 2006), similar in size to the 1855 Wairarapa earthquake. Our aim is to identify the long-term vertical deformation rate for Turakirae Head so that it can be compared with the uplift value measured for the 1855 Wairarapa earthquake and then scaled to (and subtracted from) the long-term Hutt Valley subsidence rate calculated from drillhole data.

Subs_{WgF} is the subsidence rate attributable to movement on the Wellington Fault; it is resolving this term that is the primary focus of this paper.

“Other” is a factor for possible additional influences on long-term vertical deformation (e.g. subduction interface-related deformation) that may impact on the Hutt Valley, but are currently not quantified.

Most of the variables have a range of uncertainties, which we propagate through our calculation using a logic tree structure (Fig. 2) (e.g. Kulkarni et al. 1984) to derive values of per event subsidence at the locations of drillhole data (Fig. 3). Key parameters used in the logic tree are listed below and covered in detail in Townsend et al. (2015):

- Hutt Valley long-term subsidence rate ($Subs_{HV}$)
- Wairarapa Fault recurrence interval, derived primarily from:
  - Turakirae Head Single Event Vertical Displacement (SEVD)
  - Turakirae Head long-term (Holocene) uplift rate ($Subs_{Turak}$)
- Hutt Valley uplift driven by Wairarapa Fault ($SEVD_{1855HV}$)
- Wellington Fault recurrence interval (WgF RI)

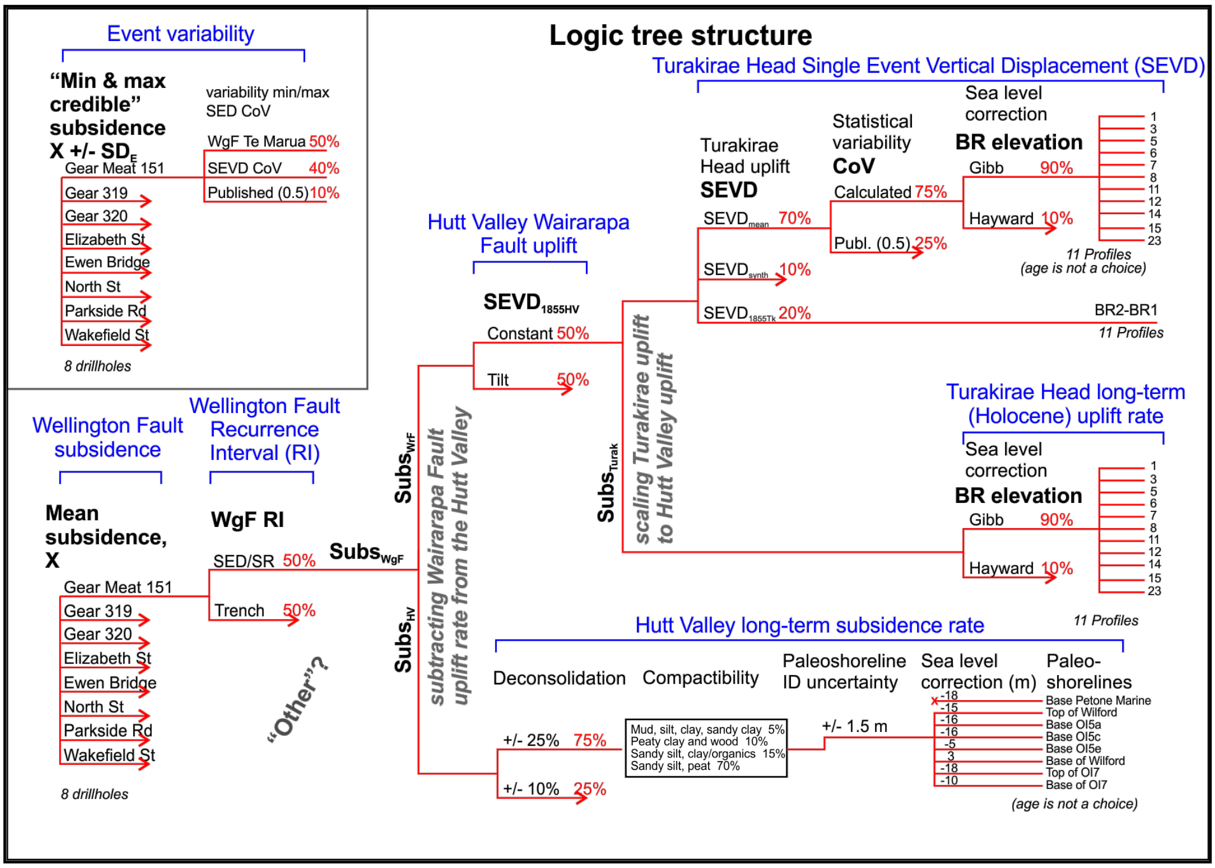

Figure 2. Logic tree used for estimating co-seismic subsidence in the lower Hutt Valley resulting from Wellington Fault rupture. Only one full branch is shown for clarity; red arrows indicate continuation of other branches and percentages listed in red are weightings applied to specific logic tree branches.

The scaled contribution of vertical deformation rate from the Wairarapa Fault ($Subs_{WrF}$) is removed from the Hutt Valley subsidence rate to yield the contribution from the Wellington Fault ($Subs_{WgF}$) at each drillhole location (+/- Other). By incorporating the recurrence interval of the Wellington Fault (WgF RI), as independently determined by trenching studies (Langridge et al. 2009, 2011; Rhoades et al. 2011) and by measurements of displaced and dated geomorphic features (Little et a. 2010, Ninis et al. 2013) with the subsidence rate, a single event vertical displacement, or co-seismic subsidence per event, for the Wellington Fault can be determined at the location of each drillhole used.

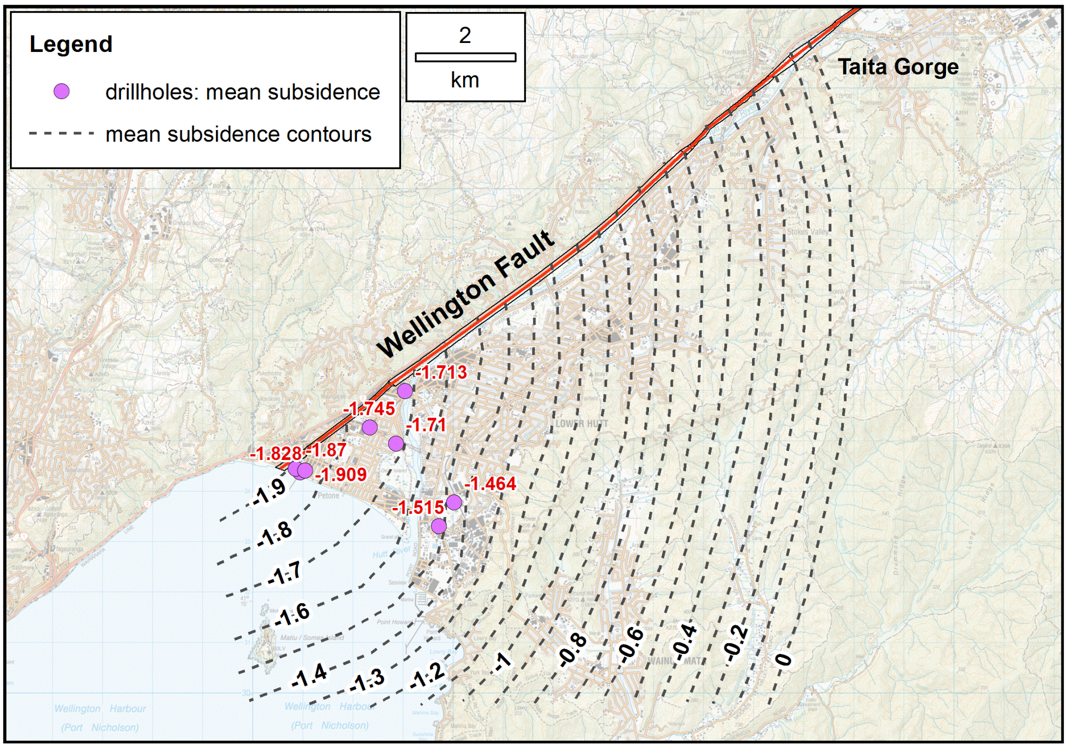

Figure 3. Drillhole locations and contours of mean co-seismic subsidence (in metres) resulting from rupture of the Wellington Fault.

Subsidence in the Hutt Valley Resulting from a Wellington Fault Rupture

Estimates of mean per event subsidence in the lower Hutt Valley resulting from rupture of the Wellington Fault range from ~1.9 m near Petone, ~1.7 m up-valley near Wakefield St, Ewen Bridge and in the central part of the valley near Marsden St, and ~1.5 m in the eastern side of the valley near Seaview. These co-seismic subsidence values are an estimate of permanent ground deformation expected in association with an "average" Wellington Fault surface rupture event. Like Begg et al. (2002), we assume "zero" differential displacement across the Wellington Fault at Taita Gorge because at this location bedrock is exposed on both sides of the fault. The subsidence values have been manually contoured to honour the data points and to bring the orientation of the far-field contours sub-parallel to the strike of the fault (Fig. 3). These contours have been interpolated into a digital surface model, which has then been subtracted from the LiDAR digital terrain model (DTM) to produce a "digital future model" (DFM) of topographic elevations. The resulting zero metre elevation contour is shown on Figure 4 as a blue line surrounding areas that would subside below current sea level during an "average" event. Such a distribution of vertical deformation would result in large areas of Alicetown-Petone and Moera-Seaview subsiding below sea level.

The mean subsidence produces topography similar to pre-1855 elevations (i.e., elevations prior to the Wairarapa earthquake uplift in 1855), but with comparatively lower elevations immediately east of the Wellington Fault and higher elevations in the eastern side of the valley (compare blue and green lines on Figure 5). This is due to subsidence resulting from a Wellington Fault rupture being more localised to the Hutt Valley compared with uplift on the Wairarapa Fault being more regional in effect (e.g. Grapes & Downes 1997; Townsend et al. 2015).

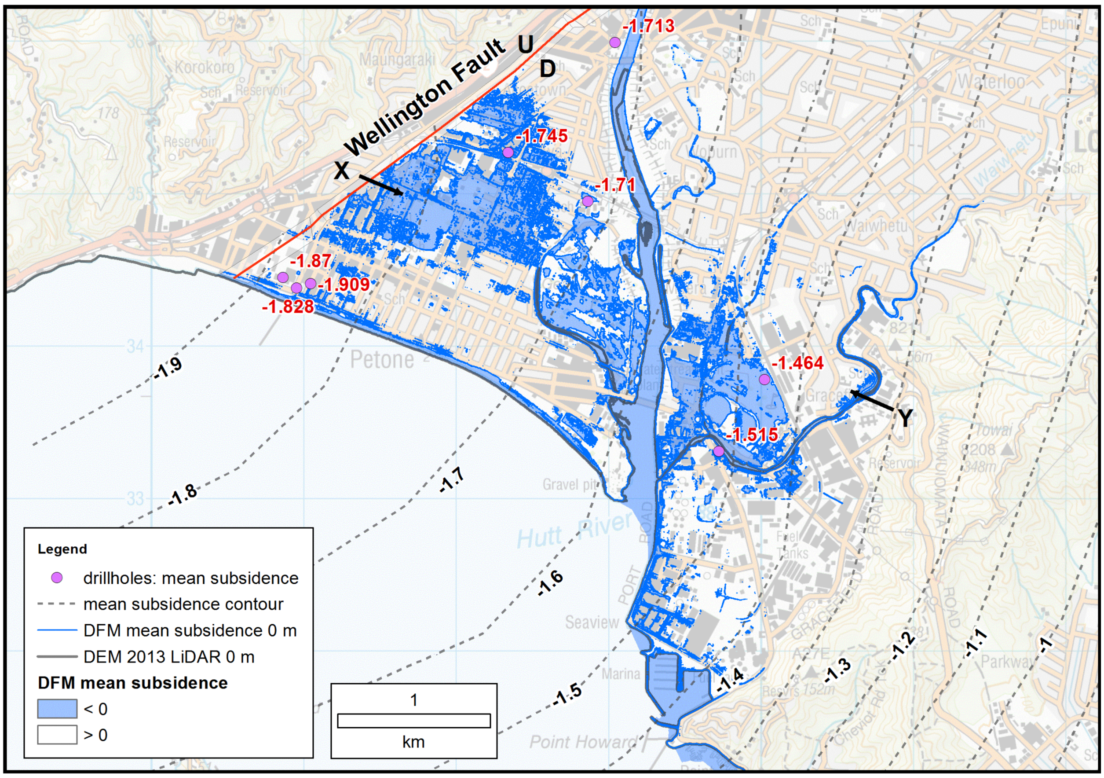

Figure 4. Subsidence value contours (dashed black lines, in metres) for an “average” Wellington Fault rupture. See Figure 5 for Profile X-Y.

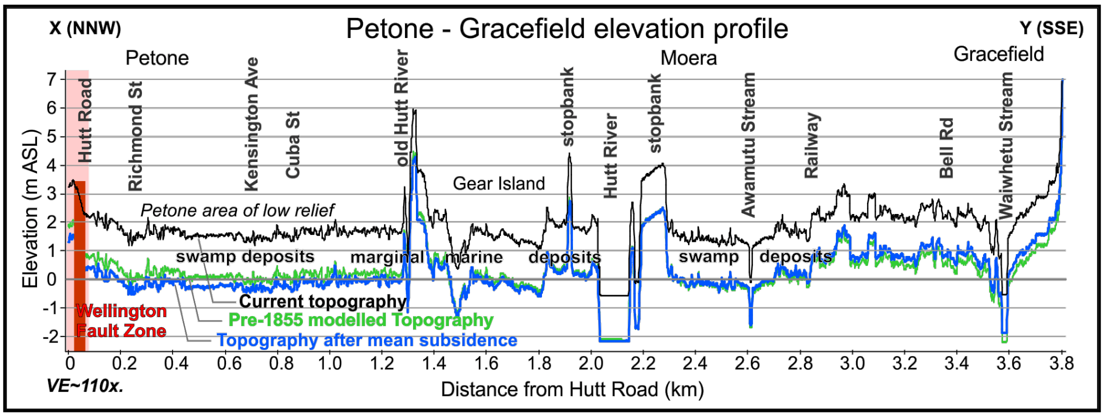

Figure 5. Topographic profile across the lower Hutt Valley (located on Fig. 4) based on LiDAR data. Black line shows current topography; blue line shows topography with mean Wellington Fault co-seismic subsidence subtracted, and green line is based on a reconstruction of pre-1855 Wairarapa Fault earthquake land levels.

The above analysis is an attempt to quantify the mean per event subsidence associated with the Wellington Fault. However, future rupture events have potential variability about the mean value. We attempt to capture this variability through the various parameter uncertainties and branch weightings used in the logic tree (Fig. 2). From this, a standard deviation (SD_E) about the mean value can be estimated to describe a likely size range of future subsidence events.

We calculated values for the mean +/- 1 SD_E, contoured and subtracted topography as above (Fig. 6). The uncertainties carried through our calculations produce a large range in forecast SD_E values. Sensitivity analysis indicates that the parameters for the Wellington Fault recurrence interval and single event displacement contribute the most uncertainty. In a “best case” scenario describing the minimum credible per event subsidence, the Petone area would experience ~1 m of subsidence, with smaller amounts up valley and to the east (Fig. 6A). This would mainly impact low-lying areas adjacent to the Hutt River and its tributaries by impairing drainage. In a “worst case” scenario (Fig. 6B), the Petone area would experience a ~2.8 m drop, with ~2.5 m up valley and 2.2 m in the east, with large parts of the lower Hutt Valley subsiding below current sea level.

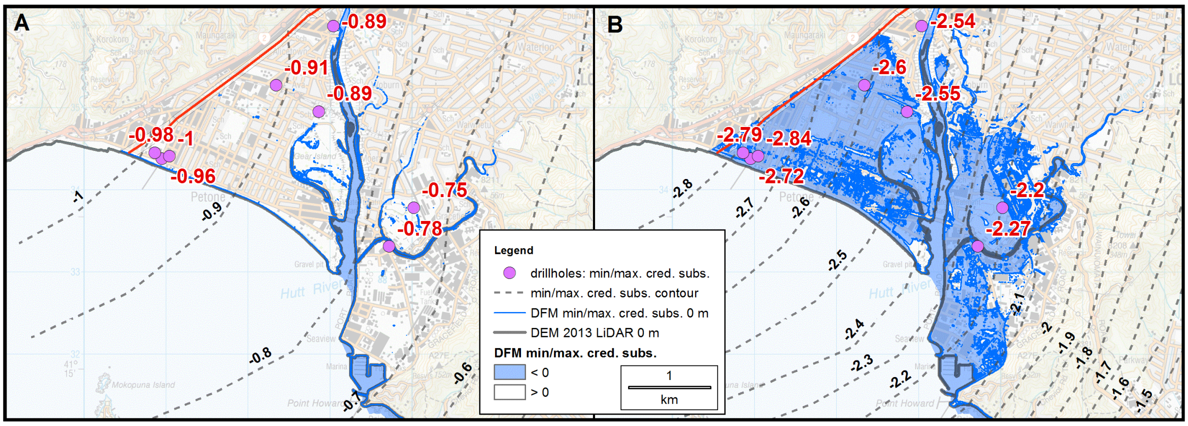

Figure 6. A) minimum credible subsidence (mean – SD_E) is about 1 m near Petone and lesser amounts up valley and to the east. B) maximum credible subsidence (mean + SD_E) results in about 2.8 m near Petone, 2.6 m up valley and about 2.2 m in the east of the valley.

Societal Implications and Conclusions

Because much of the lower Hutt Valley area is low-lying and within a few metres of current sea level, metre-scale subsidence will potentially have catastrophic consequences. Projected climatically driven sea level rise will only exacerbate this problem. We are currently working with Greater Wellington Regional Council and Hutt City Council to develop a suite of possible mitigation strategies with the goal of increasing resilience and limiting future losses. Possible mitigation measures could include: review of the Hutt City plan to assess what additional planning measures may be required to mitigate risk to society; plan for a managed retreat of critical facilities; limiting development; pre-event recovery planning for land use; updating emergency management plans; raising awareness and educating decision makers; and treating this information within the context of other natural hazards that may affect the area.

Despite historical uplift, the long-term vertical deformation signal in the lower Hutt Valley is subsidence. Using surface and sub-surface geological information, we derive values of per event subsidence expected for an “average” Wellington Fault surface rupture, as well as minimum and maximum credible values. Mean per event subsidence values are ~1.9 m in the west near Petone, ~1.5 m in eastern Hutt, and ~1.7 m up valley at Ewen Bridge.

Our modelling of the landscape change resulting from this subsidence uses digital elevation models based on LiDAR data. For an “average” Wellington Fault event, large parts of Alicetown-Petone and Moera-Seaview would subside below sea level; the landscape in the lower Hutt Valley would be similar to that prior to the ~1.4 m uplift associated with the 1855 Wairarapa earthquake.

Uncertainty in data and/or variation derived from alternative interpretations is carried through our calculations using weighting factors within a logic tree. Of the parameters we considered, uncertainty in the recurrence interval of the Wellington Fault is the major contributor to the variation in subsidence between the “minimum credible” and “maximum credible” values.

Acknowledgments

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