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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. 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 lower Hutt Valley of the Wellington region, New Zealand, 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.

In 1855 the M_w ~8.2 Wairarapa Earthquake resulted in uplift of the lower Hutt Valley area and created an expectation that future earthquakes would do the same. However, sediments beneath the lower Hutt Valley floor up to c. 220 thousand years old provide data that when combined with the international sea-level curve demonstrate cumulative net subsidence of up to c. 155 m during that period. Recent refinement of rupture parameters for the Wellington Fault (and other faults in the region), based on new field data, has spurred us to reassess estimates of vertical deformation in the Hutt Valley that would result from rupture of the Wellington Fault. Using a logic tree framework, we calculate subsidence for an “average” Wellington Fault event of ~1.9 m near Petone, ~1.7 m near Lower Hutt City, ~1.4 m near Seaview, and ~0 m in the Taita area. Such a distribution of vertical deformation would result in large areas of Alicetown-Petone and Moera-Seaview subsiding below sea level. We also calculate and present “minimum” and “maximum” credible subsidence values, which are approximately half and twice the mean values, respectively. This ground deformation hazard certainly has societal implications, and we are working with local and regional councils to develop a range of mitigation strategies.

INTRODUCTION

The area of the 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 (Figure 1). It is part of a sedimentary basin that includes geologically young (< 1 Ma), relatively soft sediment deposited in the lower reaches 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. [4]). 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. [3, 5, 6]) based on evidence from geomorphology and drill-hole data from the Hutt Valley, and seismic refraction survey 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 refraction surveys of Wellington Harbour reveal a stratigraphy that has been tilted westward towards the Wellington Fault, implying that the harbour is situated within a fault angle depression [7]. Furthermore, the sediments imaged in seismic refraction profiles beneath the harbour floor are increasingly deformed in proximity to the fault, implying that the Wellington Fault is a key driver of basin subsidence.

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 [8] was for local and regional authorities to work to recognise areas of high potential hazard and mitigate their impacts. Importantly, for low-lying urban areas near active faults, such as Lower Hutt, the 22 February, 2011 M_w 6.2 Christchurch earthquake highlighted the potential for earthquake-induced subsidence and flooding to adversely impact the urban environment (e.g. [9, 10]).

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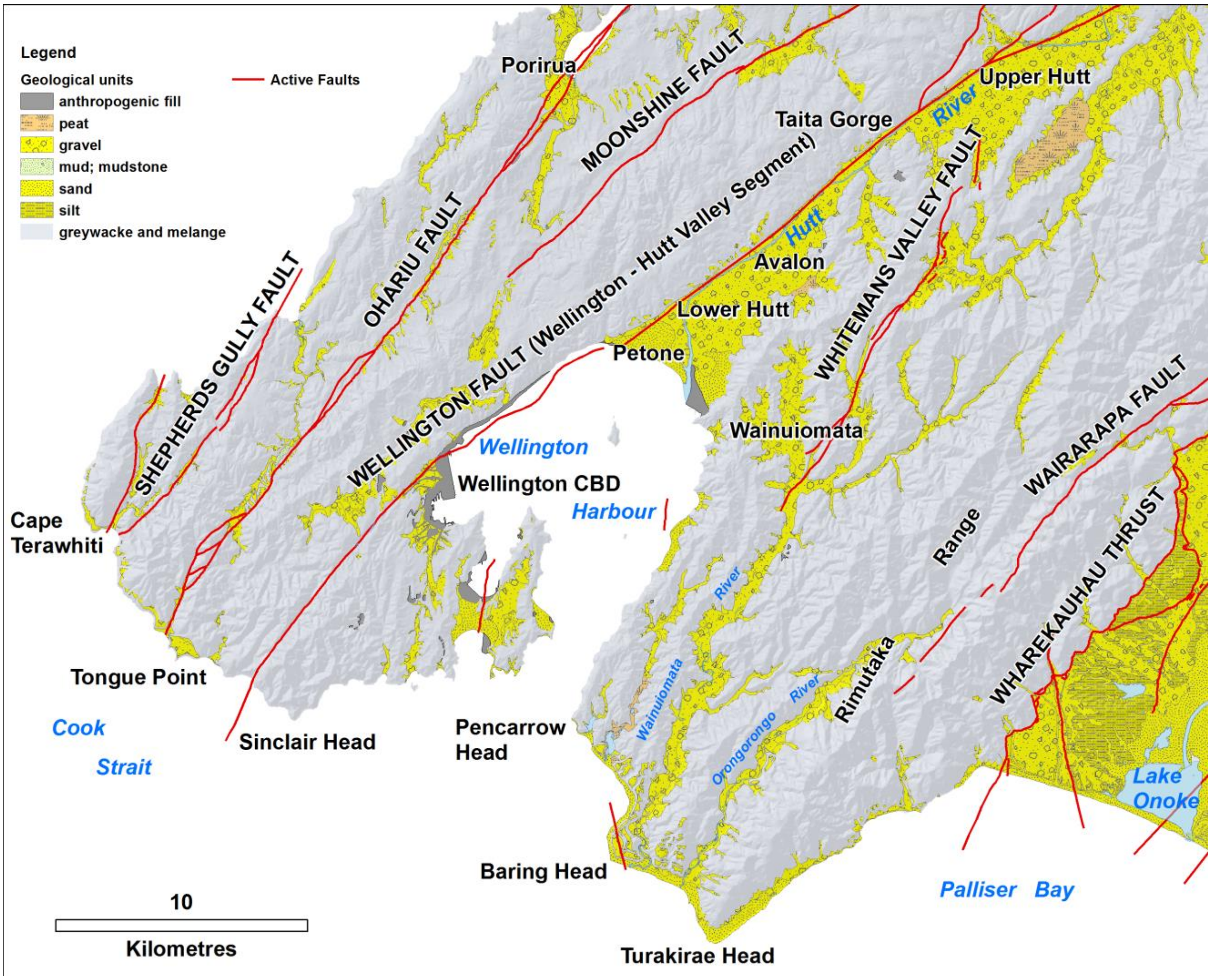

Figure 1: Location of the lower Hutt Valley in the Wellington Region, with active faults from GNS Active Fault Database [1, 2]. Digital geology base layer from Begg & Mazengarb [3].

The Wellington Fault is dominantly strike-slip in character, but associated deformation involves a changing component of dip-slip displacement along its strike (e.g. [3, 5]). The variable nature of this displacement is highlighted by the elevations of the K-Surface (Figure 2), an ancient erosion surface cut into the greywacke bedrock (e.g. [3]). The existence of Wellington Harbour, the mid-late Quaternary deposits in the lower Hutt Valley and the Upper Hutt basin is entirely attributable to cumulative vertical displacements along the southeast side of the Wellington Fault.

A method for calculating co-seismic subsidence in the lower Hutt Valley as a result of Wellington Fault rupture was proposed by Begg et al. [5, 6]. Drill-hole logs for the lower Hutt Valley record a stratigraphy that includes three shelly, marine incursions with warm climatic palynofloras within materials dominated by cool climatic alluvial deposits [11]. These stratigraphic units thicken towards the west of the valley, being greatest close to the Wellington Fault. The stratigraphy is interpreted to result from semi-continuous deposition during on-going deformation through the fluctuating climatic cycles of the middle and late Quaternary (e.g. [3, 5, 6]). Stratigraphic boundaries between marine and non-marine units represent paleoshorelines. When coupled with the international sea level curve (e.g. [12]), these data indicate on-going subsidence through the lower Hutt Valley, with greater rates of subsidence close to the Wellington Fault, resulting in progressive north-westward paleoshoreline tilting with age. Vertical deformation in the lower Hutt Valley potentially incorporates components from rupture of the Wellington and Wairarapa faults, and from other faults including the subduction interface, and also sediment consolidation. Readers of this paper are referred to Townsend et al. [17] for explanation and quantification of potentially significant components of on-going vertical deformation.

Two of the key data inputs for Begg et al.'s calculations were the earthquake recurrence intervals of the Wellington and Wairarapa faults. Investigations undertaken through the It's Our Fault project have yielded new estimates of these recurrence intervals (e.g. [13-16]); thus a re-appraisal is warranted of Wellington Fault-driven co-seismic subsidence.

This paper presents an abridged account of the re-evaluation by Townsend et al. [17] of subsidence hazard in the lower Hutt Valley posed by a future rupture of the Wellington Fault. Incorporating updated data for the Wellington and Wairarapa faults, along with careful quantification of associated uncertainties through a logic tree structure (Figure 3; e.g. [18]), has allowed for a robust estimation of credible mean, minimum and maximum values for co-seismic subsidence. 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).

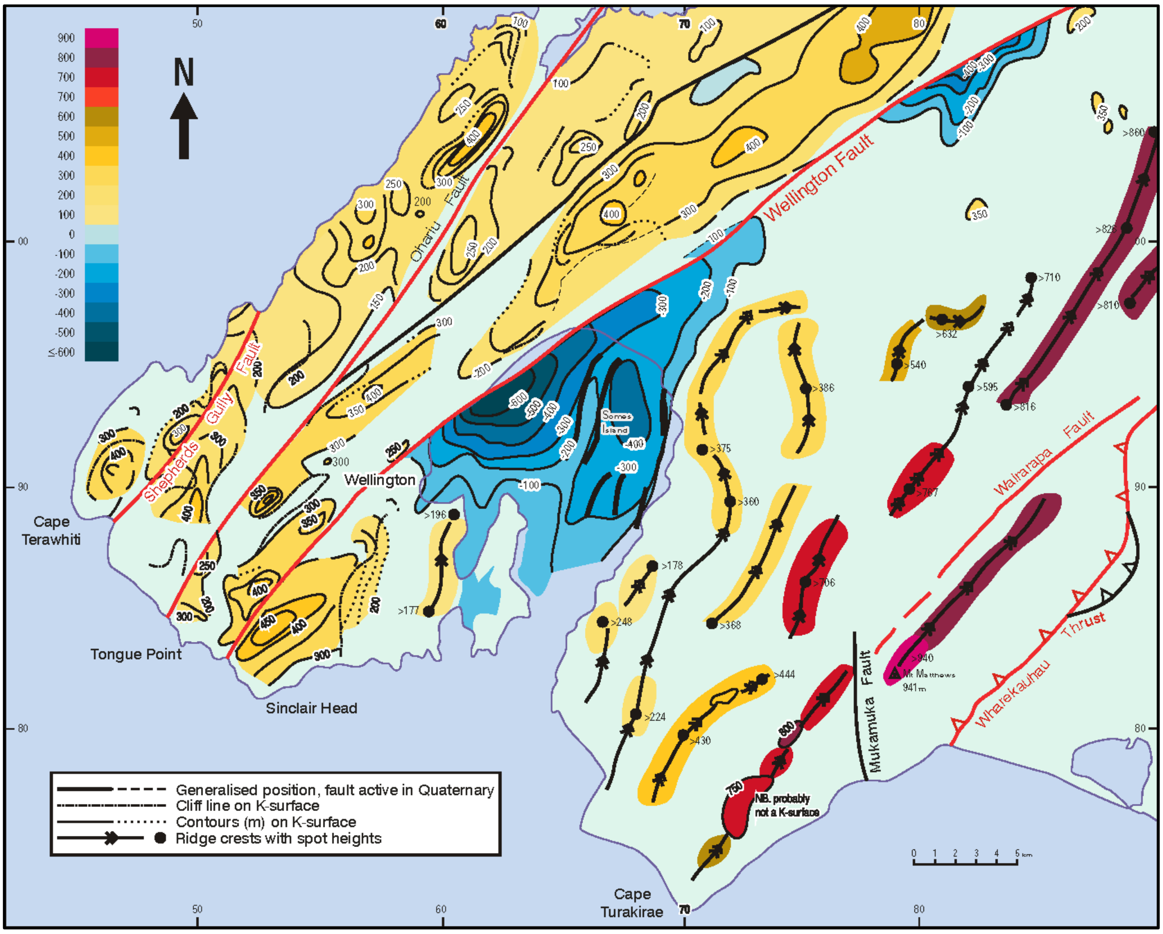

Figure 2: Approximate structure contours on the K-Surface. Note the consistent elevation on the northwest side of the Wellington Fault and the rapid changes in elevation southeast of the fault. After Begg et al. [5].

Potential societal and land-use planning issues 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 drill-hole data obtained from deposits of the last several hundred thousand years, are given in Townsend et al. [17]. 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 Street, ~0.6-0.7 mm/yr at Marsden Street and in the central part of the valley near Lower Hutt City, and ~0.3-0.5 mm/yr in the eastern side of the valley near Seaview. All of these cumulative subsidence estimates 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 drill-holes [17].

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 (Figure 1) to assess slip characteristics such as recurrence interval (RI) and single event vertical displacement (SEVD) on the Wairarapa Fault. Turakirae Head beach ridges record evidence of pre-historic earthquakes (at least four in the last ~8,000 years [19]) 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 drill-hole data.

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

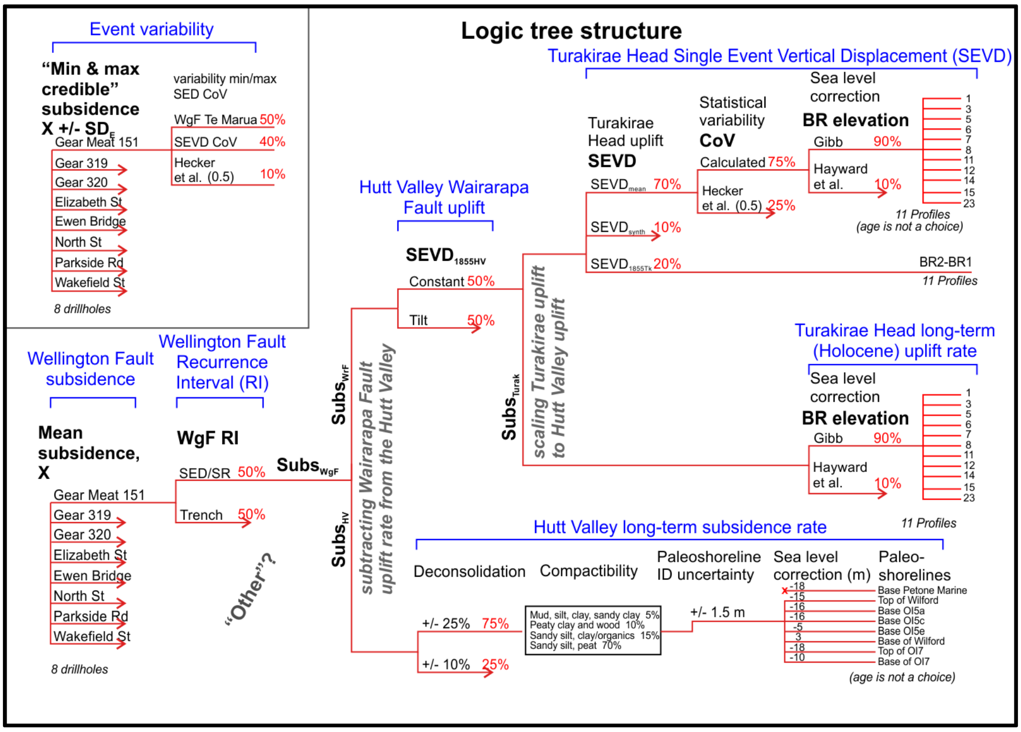

Figure 3: Logic tree used for estimating co-seismic subsidence in the lower Hutt Valley resulting from Wellington Fault rupture [17]. Only one full branch is shown for clarity; arrows indicate continuation of other branches and percentages listed are weightings applied to specific logic tree branches. References cited in figure are: Gibb [23], Hayward et al. [24], and Hecker et al. [25].

"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. In our results presented below, we set "Other" equal to 0. An implication of this, for example, is that we assume that the long term vertical deformation signal in the Hutt Valley due to movement on the Hikurangi subduction interface is largely neutral. That is, we assume that any co-seismic vertical deformation resulting from subduction zone rupture is largely recovered during the inter-seismic period (e.g. [20 - 22]). While this assumption simplifies our calculations below, it certainly needs to be tested for the Wellington region and the Hikurangi subduction zone.

Most of the variables we consider have a range of uncertainties, which are propagated through our calculations using a logic tree structure (Figure 3) (e.g. [18]) to derive values of per event subsidence at the locations of drill-hole data (Figure 4). Key parameters used in the logic tree are listed below and covered in detail in Townsend et al. [17]:

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

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 drill-hole location (+/- Other). By incorporating the recurrence interval of the Wellington Fault (WgF RI), as independently determined by trenching studies [15, 26, 27] and by measurements of displaced and dated geomorphic features [28, 29] with the calculated subsidence rate, a single event net vertical displacement, or co-seismic subsidence per event, for the Wellington Fault can be estimated at the location of each drill-hole used [17].

SUBSIDENCE IN THE HUTT VALLEY RESULTING FROM A WELLINGTON FAULT RUPTURE

Employing the logic tree structure outlined in Figure 3 and the variables encompassed by equation (1), calculated 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 Street and Marsden Street, and ~1.5 m in the eastern side of the valley near Seaview (Table 1, Figure 4). 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. [5], 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 (Figure 4). 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 5 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 single event 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 profiles on Figure 6). This is due to subsidence resulting from a Wellington Fault rupture being more localised to the Hutt

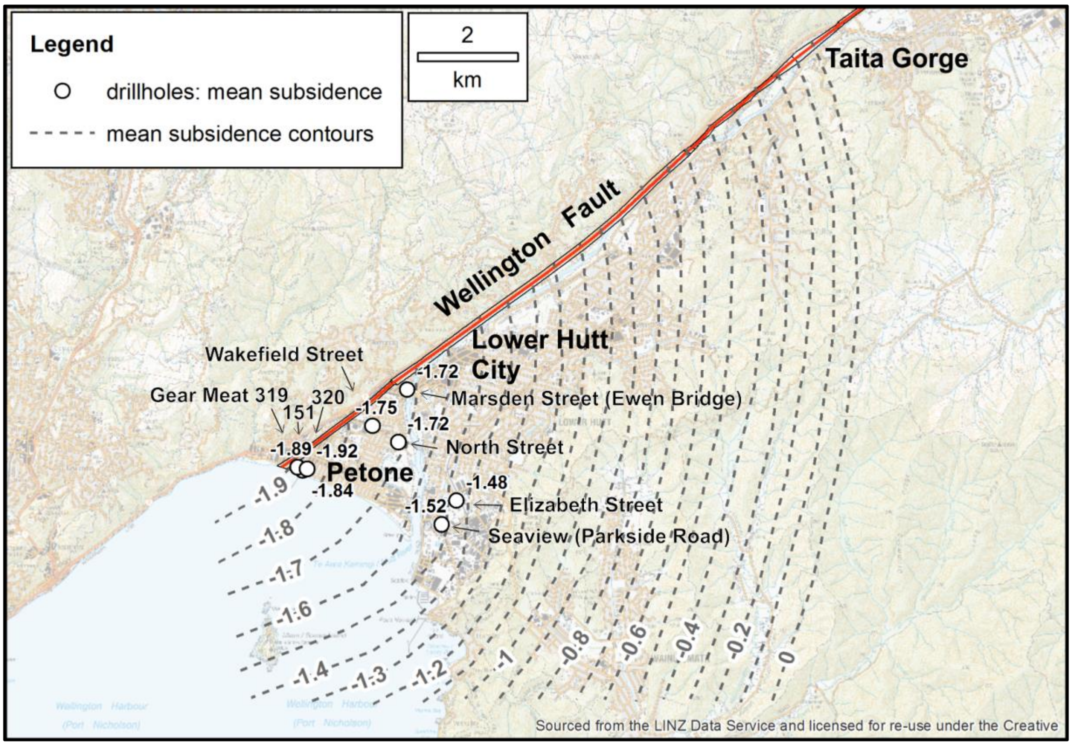

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Figure 4: Drill-hole locations and contours of mean co-seismic subsidence (in metres) for modelled rupture of the Wellington Fault.

Valley compared with uplift on the Wairarapa Fault being more regional in effect (e.g. [4, 17]). Additionally, these modelled land-level changes do not account for the possible local effects of subsidence resulting from liquefaction or lateral spreading (which would require a separate modelling exercise), or from the consequent removal of liquefaction ejecta, both of which significantly contributed to net subsidence in Christchurch following the Christchurch earthquake [9, 10].

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 (Figure 3). 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 (Figure 7). The uncertainties carried through our calculations produce a large range in forecast SD_E values. Sensitivity analysis indicates that the estimates of the Wellington Fault recurrence interval and single event displacement contribute the most uncertainty (Table 2). 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 (Figure 7A). This would mainly impact low-lying areas adjacent to the Hutt River and its tributaries by impairing drainage. In a “worst case” scenario (Figure 7B), 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.

Table 1: Mean and Standard Deviation (averaging across profiles) of subsidence per event calculated for a Wellington Fault rupture at the location of each Hutt Valley drill-hole.

Drill-hole Location	Mean Subsidence Per Event (m)	Standard Deviation (m)
North Street	1.72	0.54
Gear Meat 151	1.84	0.58
Gear Meat 319	1.89	0.59
Gear Meat 320	1.92	0.60
Wakefield Street	1.75	0.55
Seaview (Parkside Rd)	1.52	0.50
Elizabeth Street	1.48	0.49
Marsden Street (Ewen Bridge)	1.72	0.54

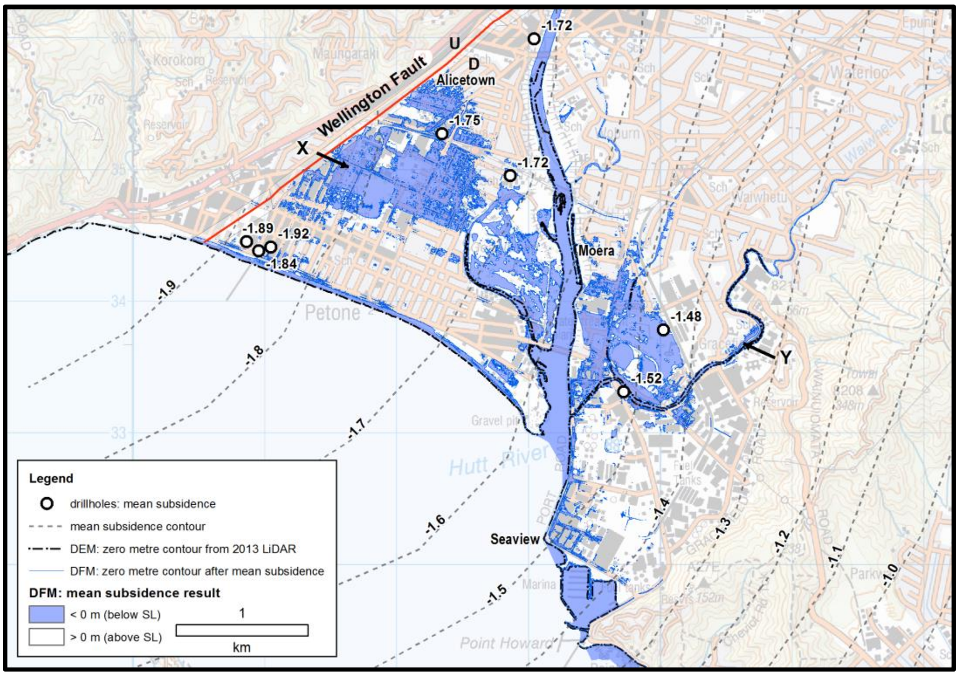

Figure 5: Shaded (blue) areas show regions that are modelled to subside below current sea level during an "average" Wellington Fault rupture. Dashed grey lines are subsidence contours (in metres) from Figure 4. See Figure 6 for Profile X-Y.

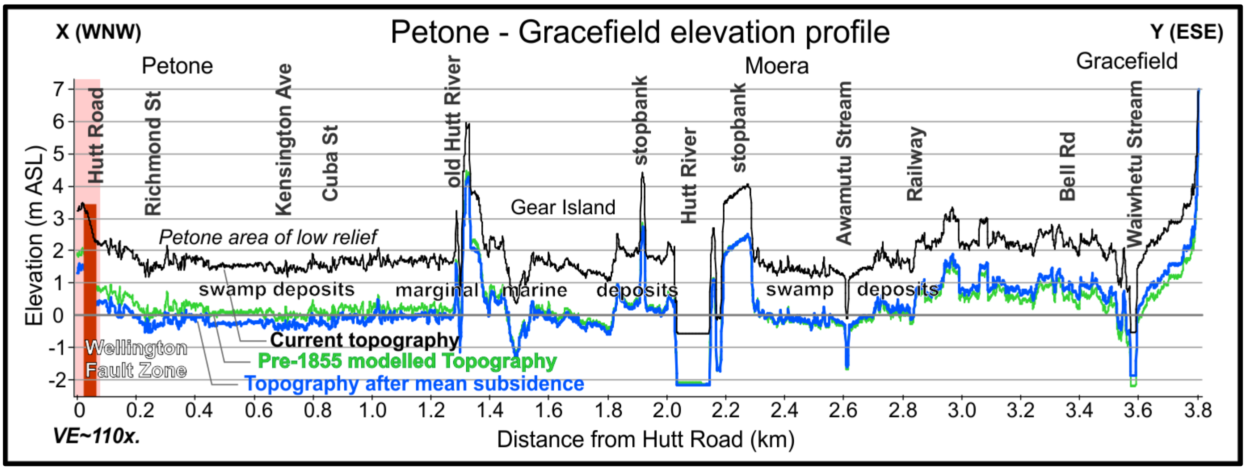

Figure 6: Topographic profile across the lower Hutt Valley (located on Figure 5) based on LiDAR data ("Current topography"); also shown is the topography with mean Wellington Fault co-seismic subsidence subtracted, and topography based on a reconstruction of pre-1855 Wairarapa Fault earthquake land levels.

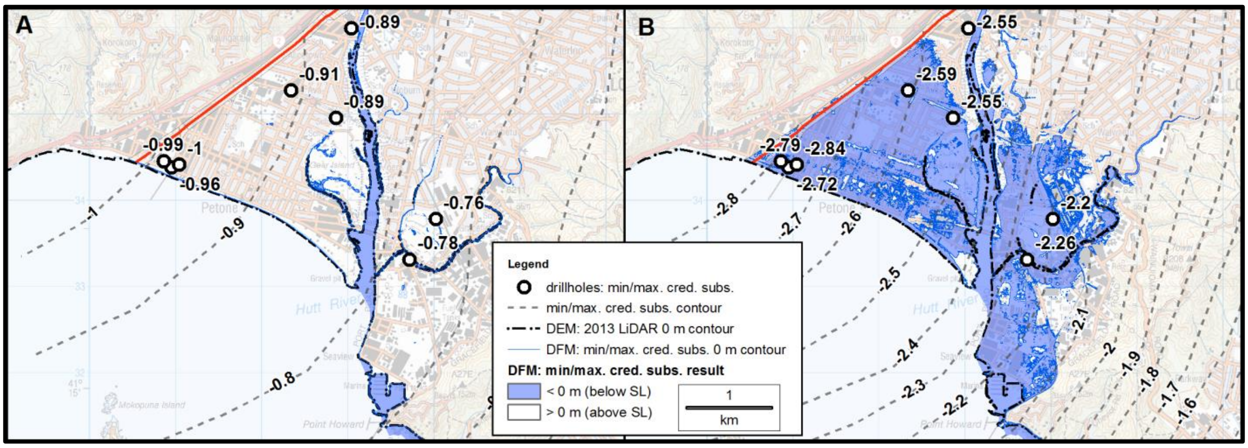

Figure 7: A) minimum credible subsidence (mean – SD_E) is about 1 m near Petone and lesser amounts up valley and to the east. B) maximum credible subsidence (mean + SD_E) results in about 2.8 m near Petone, 2.6 m up valley and about 2.2 m in the east of the valley.

Table 2: The average subsidence value for all drill-holes (1.72 m) is used to compare the sensitivity of input variables in the logic tree. The larger the values of "difference from mean" are the more impact that that variable has on the final result; see Townsend et al. [17] for full explanation.

Branch or variable	Subsidence (m)	Difference from mean (m)	Logic tree weight (%)
Deconsolidation +10%	1.72	0.00	25
Deconsolidation +25%	1.72	0.00	75
RSL from Gibb [23]	1.72	0.00	90
RSL from Hayward et al. [24]	1.75	-0.03	10
WgF RI from SED & SR	1.26	0.46	50
WgF RI from trench data	2.18	-0.46	50
WrF CoV calculated	1.72	0.00	75
WrF CoV from Hecker et al. [25]	1.72	0.00	25
Turakirae SEVD$_{1855Tk}$	1.64	0.08	20
Turakirae SEVD$_{mean}$	1.68	0.04	70
Turakirae SEVD$_{synth}$	2.16	-0.44	10

RSL: Relative Sea Level; WgF: Wellington Fault; SED: Single Event Displacement; SR: Slip Rate; WrF: Wairarapa Fault; CoV: Coefficient of Variation; SEVD: Single Event Vertical Displacement.

SOCIETAL IMPLICATIONS AND CONCLUSIONS

Because much of the lower Hutt Valley area is low-lying – within a few metres of current sea level – metre-scale single event subsidence has potentially 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 impact on 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. These measures are discussed in more detail in Townsend et al. [17].

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 near Lower Hutt City.

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. We also calculate "minimum" and "maximum" credible subsidence values, which are approximately half and twice the mean values, respectively. Uncertainty in data and/or variation derived from alternative interpretations is carried through our calculations using weighting factors within a logic tree. Of the input data that we employed, 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.

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