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The ups and downs of coastal regions: The implications of vertical land motion on coastal hazards

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ABSTRACT

More than 10% of the world's population (~600 million people) live in the coastal zone that is within 10 metres of sea level. The combination of global sea level rise (SLR) of 2-3 mm/yr, and late 20th century sea level acceleration, makes coastal communities in many parts of the world vulnerable to gradual inundation that will, in the future, require either adaptation or retreat from affected coastlines. Although the measurement and monitoring of SLR is well established through a combination of globally distributed tide gauge sites and altimeter measurements; what is not well understood is local and regional geodynamical process that result in vertical land motion (VLM) that has the potential to increase coastal hazard.

Often the VLM trend is slow and imperceptible. For example, VLM associated with glacial isostatic adjustment (Scandinavia, North America) are predictable while VLM associated with water and gas extraction (Australia, USA, Malaysia) are not. In the case of seismic activity, VLM associated with an earthquake event can be unpredictable and cause vertical displacements of up to several metres. Other types of seismic activity, such as postseismic deformation or periodic slow slip events may result in gradual subsidence or uplift VLM over extended periods of time.

New Zealand straddles the Australian/Pacific plate boundary and we are just starting to realise the spatial and temporal complexities associated VLM. GPS/GNSS measurements have been used to monitor the Hikurangi subduction zone (east coast of the North Island) that has resulted in a combination of subsidence (2-5 mm/yr) and slow slip events (1 mm/yr uplift). The recent Kaikōura 2016 earthquake resulted in spatially coherent coseismic displacements that caused subsidence in the Wellington region of 30 mm followed by ongoing postseismic deformation that has uplifted the region by up to 50 mm. In low lying areas of Christchurch we have measure subsidence of 10 mm/yr following the Christchurch 2011 earthquake events. In seismically activate regions and especially coastal zones close to tectonic plate boundaries, VLM needs to be monitored and included in SLR studies to understand the geodynamics that is affecting the coastal regions hazard and risk assessments.

I. INTRODUCTION

Sea level is a global indicator of incremental change of the volume of ocean water caused by, for example, global warming that is largely attributed to melting land ice and thermal expansion due to warming of the ocean. In addition, the change in local sea level is affected by vertical land motion (VLM) due to subsidence/uplift caused by groundwater or oil extraction, glacial isostatic adjustment or tectonic movements. As tide gauges measure relative sea level rise, absolute sea level rise estimates must take VLM into account. Geodetic position time series measured using GNSS is a commonly used method to estimate VLM.

New Zealand is a prime example of tectonically induced deformation. In recent years, particular attention has been made to the horizontal deformation (e.g. Beavan et al., 1999, 2007; Wallace et al., 2007). The secular horizontal deformation field is now well established and is routinely incorporated in regional and national survey work (e.g. Winefield et al., 2010; Crook and Donnelly, 2013; Beavan et al., 2016) and the maintenance of the national geodetic system (e.g. Blick et al., 2003; Pearson et al, 2015). What is less well understood is the (generally) short term transient deformation caused by slow slip events (SSE) (Douglas et al., 2005, Wallace et al., 2010, 2012).

New Zealand's location straddling the Australian-Pacific plate boundary results in major earthquake events. In the last 10 years there have been several major earthquakes that have affected New Zealand. The Dusky Sound M_w 7.8 2004 (Fiordland SW NZ) event results in >1 m level horizontal deformation and 10 cm vertical deformation (Beavan et al., 2010b), but the postseismic deformation has continued to affect the lower half of the South Island by up to 3 mm/yr (Denys and Pearson, 2015).

The four major earthquake of the Darfield/Christchurch 2010-11 events results in >4 m horizontal and ~0.5 m vertical deformation (Kaiser et al., 2012). This was followed by the Kaikōura M_w 7.8 2016 event that rupture over 170 km and resulted in horizontal and vertical deformation of >8 m (Hamling et al., 2017). The Kaikōura 2016 earthquake also triggered a SSE that lasted for approximately two weeks (Wallace et al., 2018). Clearly, all of these events result in significant VLM, which need to be accounted for in SLR estimates from tide gauge (and other) measurements.

II. NEW ZEALAND’S TECTONIC SETTING

The collision between the Australian and Pacific plates creates the geographical and topographical features of New Zealand. At the southern end of the country, the Australian plate is subducting under the Pacific plate. The plate boundary is offshore in the deep Tasman trench with the Fiordland mountains sitting above the subducting plate (Barth et al., 2013; Page et al., 2018).

In the central South Island, the plate boundary transforms to oblique strike slip that has resulted in the ~400 km long Alpine fault. The small amount of compression (<10 mm/yr) has uplifted the Southern Alps by ~5-6 mm/yr (Beavan et al., 2010a). Further north, the Alpine fault separates into a series of parallel faults (the Marlbourgh Fault Zone), which corresponds to the start of the transition to the Hikrangi trench and the east coast subduction zone.

It is along the east coast of the North Island and top of the South Island that frequent SSEs occur, which are typical of subduction zones. At the south of the North Island, the subduction zone is deeply locked resulting in transient deformation lasting for up to one year and repeating every 5-8 years. Further north, the locking is shallower and the SSEs tend to occur more quickly (days to weeks) and more frequently (15-30 months).

III. GNSS POSITION TIME SERIES ANALYSIS

A. *GNSS positioning*

The data used for this analysis comes from the national network of continuous GNSS (cGNSS) receivers operated by GeoNET[1] to monitor both regional and national deformation. This includes receivers in the PositioNZ[2] (LINZ[3]), GeoNET (natural hazard) and Tide Gauge networks. As the GNSS receivers operate continuously, the network accurately measures displacements due to plate motion, as well as events of a seismic nature e.g. earthquakes and SSEs.

The GNSS data used in this study is processed together with other GNSS sites in New Zealand, Australia, the Pacific and Antarctica. This provides a reliable connection to the International Terrestrial Reference Frame (ITRF). We use the precise GNSS data products available to correct and reduce measurement errors. The GNSS data was processed using the Bernese software package (v5.2) (Dach et al., 2015), to generate 24 hour daily position solutions. The daily solutions for each GNSS site are used to create a three dimensional geodetic position time series.

B. *Position time series analysis*

We use a matlab position time series (`pts`) script developed by Otago University to model the east, north and height (E, N, H) components of the position time series. Assuming that the GNSS site is only affected by steady state tectonic plate motion, then the model of the position (E, N, H) time series is a simple velocity term :

$$\mathrm{X}(t) = V_X(t - t_0) \qquad (1)$$

where $\mathrm{X}(t)$ = E, N, H coordinate for time t;
V_X = the coordinate component velocity;
t = time of observations, and;
t_0 = reference time.

GNSS position time series analysis is often affected by small displacements, transient motions and other positioning trends that need to be accurately modelled. The mathematical expressions used for modelling the position time series, can be found in Denys and Pearson (2015, 2016). Standard model parameters that are routinely included are:

1) *Equipment Changes:* When the GNSS equipment is changed such as the receiver and/or antenna, either because the equipment has failed or during routine equipment upgrades, a jump in the time series is observed. This is modelled as an offset.
2) *Seasonal Effects:* Sites typically show seasonal motions due to the environmental conditions, which is modelled as annual and semi-annual periodic trends.

Offsets due to changes in the GNSS equipment and cyclical seasonal motion are easily modelled since the exact time of the equipment change is known and the period of seasonal terms (1 year and 6 months) are assumed.

In tectonically active regions, as in New Zealand, the GNSS sites are affected by seismic activities of various forms. Modelling these motions can be challenging. Broadly, the seismic events are modeled in the following categories.

1) *Periodic seismic events*: These are characterised as SSEs that repeat at (reasonably)

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[1] GeoNet: www.geonet.org.nz

[2] PositioNZ: www.linz.govt.nz/data/geodetic-services/positionz

[3] LINZ: www.linz.govt.nz

regular intervals. The repeat period may be every 18-24 months (e.g. east coast of the north island, Napier and Gisborne), or over intervals of 5-8 years (e.g. Kapiti coast).

3) Coseismic deformation*:* An earthquake event typically displaces the Earth's crust almost instantly over a period of time from a few seconds to minutes. This creates an offset in the position time series that may be a few millimetres to metres in size (e.g. the Kaikōura 2016 earthquake) and is modelled as an offset. (This parameter is identical to an equipment change offset).

4) Postseismic deformation*:* If an earthquake event is sufficiently large (typically > M_w 7), then the trajectory of the Earth's crust can respond differently for a period of time following the event. The length of time that the postseismic motion occurs will vary depending upon the size of the earthquake, but can be for a few days to many years.
   - Decay: Postseismic decay is modelled as a decay function such as logarithmic, exponential or power law. These functions require a decay constant that needs to be determined a priori. Depending upon the nature of the earthquake, postseismic decay represents after-slip or viscoelastic relaxation.
   - Transient velocity: This is a linear change in direction and speed (i.e. velocity) for a period of time following the earthquake.

IV. GNSS DERIVED VERTICAL LAND MOTION

The vertical rate of a network of GNSS sites has been estimated the vicinity of Wellington. The height trend of a subset of nine, predominately coastal, sites are shown in Figure 1. The sites are approximately ordered from (LEVN) south down the Kapiti Coast, along the south coast and northwards along the east coast of the North Island (TRAV). The velocities are determined from sites with GNSS data observed between 2000-2018. The site with the shortest time period is Terawhiti (TRWH, 7.7 years).

The secular velocity rates for these sites are shown in Figure 2. Typical of subduction zones, the trend is subsidence with a range between -2.7 mm/yr and -5.7 mm/yr (Table 1).

A. *Slow Slip Events*

The east coast of the North Island, Kapiti Coast and top of the South Island are all affected by periodic SSEs that have, so far, uplifted the land over the period of time of GNSS measurements (approximately 20 years). Based on the long record cGNSS sites (e.g. PAEK), these events appear to occur every 6-8 years and last for periods of up to one year. The SSE progressively become larger from the east coast (Figure 3 lower sites) to the west coast (Figure 3 upper sites), which represents the transition from the Pacific to the Australian plates.

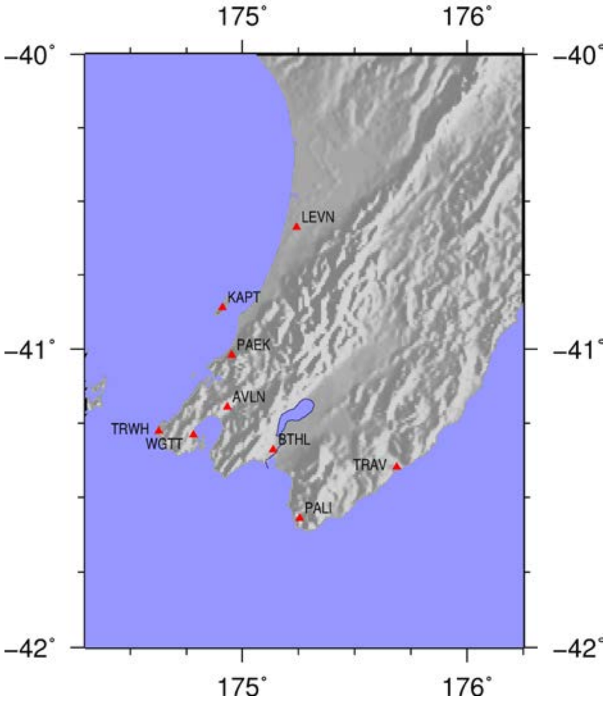

Figure 1: The nine coastal GNSS site around the greater Wellington region used in this study.

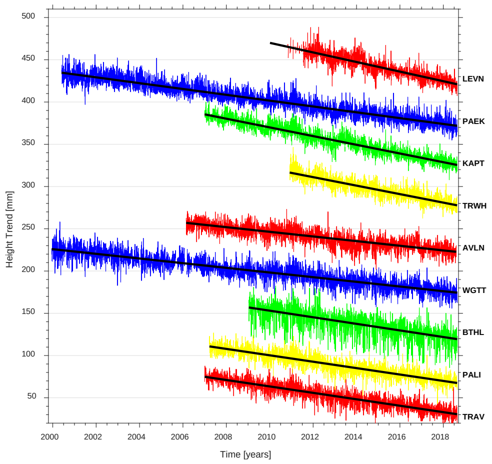

Figure 2: Height trend for North Island coastal sites with SSE, coseismic and postseismic deformation removed.

Table 1: Vertical velocity rates

Site	Velocity (mm/yr)	±σ (mm/yr)
LEVN	-5.67	0.17
PAEK	-3.45	0.12
KAPT	-5.15	0.15
TRWH	-5.02	0.18
AVLN	-2.75	0.14
WGTT	-2.69	0.12
BTHL	-3.90	0.16
PALI	-3.79	0.15
TRAV	-3.81	0.15

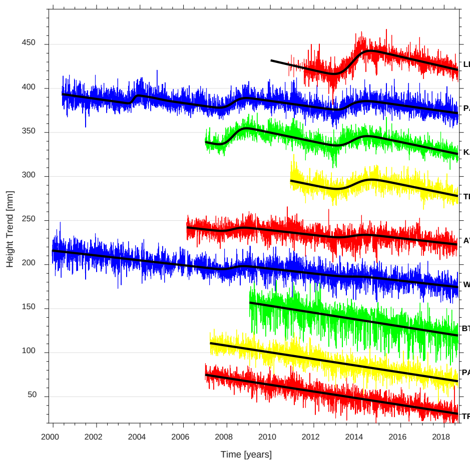

Figure 3: Height time series including SSEs that have uplifted (to date) the Australian plate relative to the Pacific plate.

Table 2: Vertical displacements for SSE since 2000. The cumulative displacement has been determined for a total of 10 years and 20 years. Of the six sites affected by SSEs, only one site has been operating for a sufficiently period of time to contribute towards the 20 year total.

Site	Total 10 years (mm)	±σ	Total 20 years (mm)	±σ
LEVN	38	4		
PAEK	32	5	41	4
KAPT	46	2		
TRWH	21	6		
AVLN	15	3		
WGTT	17	5		

Figure 3 shows the vertical displacements or offsets that have occurred over a period of nearly 20 years. The largest events have occurred in 2003, 2008 and 2013. In this case, the Kapiti Coast 2013 SSE was active for approximately 12 months.

The cumulative vertical displacement for all SSEs is given in Table 2. As the cGNSS equipment have been installed at different time periods, not all of the sites have recorded the earlier SSEs.

B. *Earthquake Events*

The Wellington region has been affected by three major earthquake events that were felt during the last five years. In addition, there was a swarm of earthquakes orginating to the west of the Kapiti Coast in late December 2014. The dates of these events are:

- Seddon 2013 Earthquakes
  - Cook Strait: 21/7/2013 2013.551
  - Grassmere: 16/8/2013 2013.622
- Wanginui Basin Swarm
  - 30/12/2014 2013.995
- Kaikōura 2016
  - 13/11/2016 2016.866

Following a major earthquake event, deformation occurs as an instantaneous displacement (coseimsic offset) followed by longer term postseismic deformation that can continue for weeks to years. As the Kaikōura earthquake was a large event, the postseismic motion is still on going after 24 months and will continue for many more years.

For the Kaikōura earthquake, the coseismic deformation has resulted in subsidence of the Wellington region (Figure 4), except for sites on the east coast of the North Island. Most sites have subsided by several centimetres (Table 3), range +10 - -30 mm.

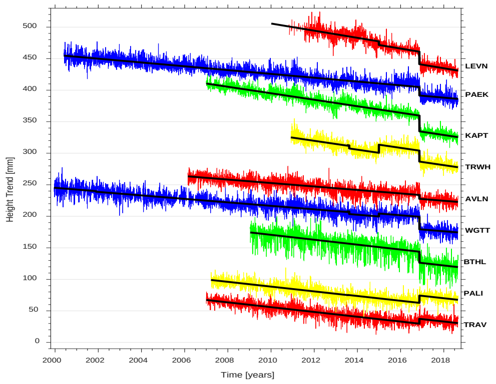

Figure 4: Height time series including the vertical coseismic displacement. Offsets can be seen for the Seddon (2013.551, 2013.622) and the Kaikōura earthquakes (2016.866).

Table 3: Vertical coseismic displacements caused by earthquake events since 2013.

Site	Coseismic (mm)	±σ (mm)
LEVN	-25	6
PAEK	-17	9
KAPT	-24	7
TRWH	-8	6
AVLN	-6	9
WGTT	-27	9
BTHL	-18	24
PALI	11	4
TRAV	5	7

The fastest postseismic motion occours immediately after the earthquake event (e.g. centimetres per month for sites on the east coast of the South Island), but gradually decreases over time. Although the postseismic deformation may be small for any single period of time, the culmulative displacement can be signficant.

Following the Kaikōura earthquake event, signficant postseismic deformation has occoured. This effect has been modelled as a logarithmic decay function plus a transient velocity term. The logarithmic function accounts for the rapidly changing velocity (direction and magnitude) following the event, while the transient velocity accounts for the longer term linear velocity change following the event.

Figure 5 shows the predominant uplift of the region following the Kaikōura 2016 earthquake. Some sites, along the Kapiti Coast, have uplifted by over 50 mm (Table 4). The postseismic deformation has therefore negated much of the subsidence caused by the coseismic deformation.

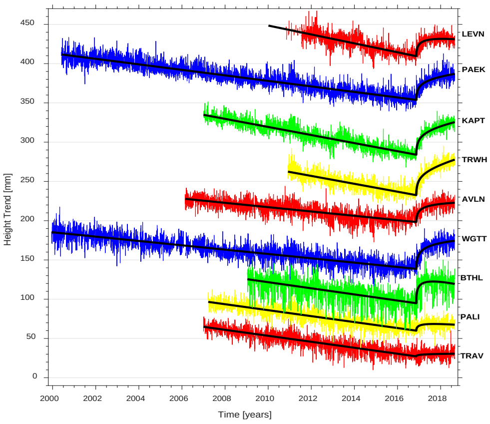

Figure 5: Height time series including the postseismic decay and velocity displacement for the Kaikōura 2016 earthquake. The coseismic has not been included.

Table 4: Cumulative vertical postseismic displacements and transient velocity displacements caused by earthquake events since 2013.

Site	Postseismic (mm)	±σ (mm)
LEVN	31	17
PAEK	38	18
KAPT	50	16
TRWH	53	16
AVLN	29	19
WGTT	40	22
BTHL	32	46
PALI	14	10
TRAV	10	15

C. *Total Displacement*

The total displacement, Δ_{Total}, experienced by coastal Wellington is the sum of the individual displacements for SSEs, coseismic and postseismic deformation (combined decay and velocity transient displacements). That is

$$\Delta_{Total} = V_X(t - t_0) + \Delta_{SSE} + \Delta_{CS} + \Delta_{PS} \qquad (2)$$

where $V_X(t - t_0)$ = secular velocity displacement
Δ_{SSE} = SSE displacement
Δ_{CS} = coseismic displacement
Δ_{PS} = postseismic displacement

The total displacements are tabulated in Table 5 and graphically shown in Figure 6. The displacement due to the long term (secular) velocity has been computed for a 10 year period (Table 5, column 6), as most cGNSS sites have been operating for this period of time.

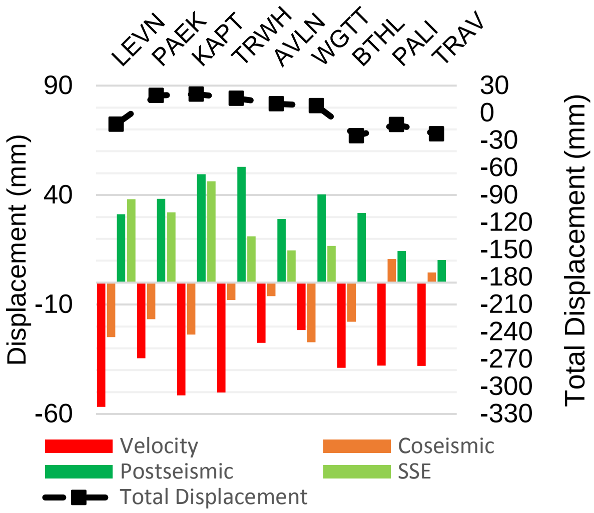

Figure 6: Vertical site displacements computed over 10 years (2008-2018). For each site, the individual displacement components (left scale) are given (secular velocity, coseismic, postseismic, SSE) and the total (cumulative) displacement (right scale).

Table 5: Total Vertical site displacements. The displacement due to the secular site velocities (mm/yr) are computed for 10 years. Displacements over these time periods are given for velocity, earthquake coseismic, postseismic (combined decay and transient velocities), and SSEs. The total displacement is the sum of the secular velocity and seismically induced displacements.

Site	Velocity (mm)	±σ	Seismic (mm)	±σ	Total (mm)	±σ
LEVN	-57	1.7	44	24	-12	25
PAEK	-35	1.2	54	27	19	27
KAPT	-52	1.5	72	24	21	24
TRWH	-50	1.8	66	24	16	24
AVLN	-28	1.4	38	29	10	29
WGTT	-22	1.1	30	32	8	32
BTHL	-39	1.6	14	69	-25	69
PALI	-38	1.5	25	14	-13	14
TRAV	-38	1.5	15	23	-23	23

It is clear that for the listed sites, the Wellington region is subsiding as a whole due to the subducting plate (Pacific) pulling the Australian plate vertically down. Vertical rates range from nearly zero to over 5 mm/yr (equivalent to 50 mm per 10 years).

Both the secular velocity and coseismic displacements were mostly subsidence (range +11 mm to -57 mm, red and orange bars, Figure 5). Conversely, the displacement due to the combined postseismic decay and transient velocity following the Kaikōura 2016 earthquake and the SSE is mostly uplift (range +10 mm to +53 mm; dark and light green bars, Figure 5).

The cumulative effect (Equation 2) is that the subsidence due to the subduction of the Pacific plate under the Australian plate plus coseismic displacement is mostly cancelled out by the current day postseismic deformation resulting from the Kaikōura 2016 earthquake and the upwards ratcheting effect of the SSEs.

The combined effect of all the displacements over the 10 year period is vertical displacements in the range of +21 mm to -25 mm (right hand scale, Figure 5 and Table 5). It is evident, for the period 2008-2018, that there is a pattern of net uplift along the Kapiti Coast of ~20 mm, decreasing to the east where the net subsidence is ~20 mm (i.e. total displacement).

In the Wellington region, there is one other site in addition to PAEK and WGTT with long cGNSS records (WGTN), where the (secular) velocity results in greater subsidence. As no significant earthquakes were observed during the initial 10 years (1998-2008), all position time series are mostly affected by the same seismic events as the cGNSS sites with the shorter position time series.

V. THE LONG TERM TREND

It is difficult to provide a definitive long term trend for any site, largely due to the effects of the recent earthquake events. What the GNSS position data does show, is that the deformation in this region is complex and is likely to remain so in the future. While the subducting plate continues to incrementally pull down both the Pacific and Australian plates, this is offset upwards by periodic SSEs and the recent Kaikōura earthquake event.

What is also clear, is that the recent major earthquake events (Seddon 2013 and Kaikōura 2016), both displaced the Wellington region. The effect of coseismic displacement was subsidence of up to 30 mm while (ongoing) postseismic displacement is causing uplift that has amount to 50 mm to date. In addition, the region is affected by the occasional SSE that (to-date) results in uplift, which has amounted to over 40 mm over 20 years.

A summary of the vertical land motion on the Wellington coastline as observed by the cGNSS sites in the lower North Island for the 10 year period (2008-2018).

1. Secular Velocity Displacement: Long term trend 2 - 5 mm/yr subsidence.
2. Coseismic Displacement: Instantaneous displacement caused by large earthquakes (Seddon 2013, Kaikōura 2016) of up to 30 mm subsidence for sites on the Kapiti Coast and up to 10 mm uplift for sites on the east coast of the North Island.
3. Postseismic Displacement: The combined effect of post seismic decay and a post-earthquake transient velocity (Kaikōura 2016) earthquake has resulted in uplift of 10 – 50 mm
4. Slow Slip Events Displacement: Based on 20 years of GNSS position time series, uplift of 0-1 mm/yr. Periodic events that appear to occur in a 5-8 years cycle results in VLM ratcheting upwards.

It is expected that the postseismic deformation will continue for many years albeit the displacement will gradually become smaller over time.

VI. SUMMARY

A network of continuous GNSS (cGNSS) stations in the greater Wellington region has measured VLM over more than ten years. The vertical velocity trend has shown that the coastline is currently undergoing subsidence at rates of up to 5 mm/yr.

However, the subduction zone induced subsidence has recently been affected by various seismic activity: SSEs, coseismic and postseismic displacements that has generated significant vertical displacements. The SSE observed to date have resulted in an average uplift of ~1 mm/yr, while the Kaikoura earthquake event resulted in a combination of coseismic subsidence and postseismic uplift for most stations

This VLM and specifically the long term subsidence is important because it significantly affects the elevations of the coastal land and thus the vulnerability of the land to coastal flooding and the risk of seawater inundation. The existence VLM along Wellington's coastline is a matter of concern because it will obviously, over time, increase the regions vulnerability to flooding, sea level rise spring tides/storm surges and tsunami events.

It is therefore important cGNSS stations be maintained and thus monitor any significant elevation changes associated with both continuous subsidence and future earthquake displacements. Any change in the vertical trend has important implications for land use planning in Wellington and the lower North Island.

VII. ACKNOWLEDGEMENTS

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