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Detecting Subsidence Using Remote Sensing Methods

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ABSTRACT

Remote sensing data from aerial surveying and satellite is of interest for environmental monitoring and was recently trialed by Waikato Regional Council (WRC) in New Zealand. This study investigates known areas of ground subsidence in Taupo, New Zealand using aerial imagery and satellite data. Results confirm subsidence is ongoing, and demonstrate the use of remote sensing methods including photogrammetry and Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) to quantify vertical surface change over time. The methods have a wide range of applications of interest to geothermal development, including reservoir modelling, and monitoring vegetation, geothermal surface features, surface subsidence and inflation.

1. INTRODUCTION

Waikato Regional Council (WRC) undertakes periodic aerial surveys of geothermal areas using crewed aircraft (Waikato Regional Aerial Photography Syndicate (WRAPS), and uncrewed aircraft systems (UAS)(Harvey et al., 2018; Harvey Geoscience, 2019). Photogrammetry processing of aerial imagery provides orthophotos, Digital Elevation Models (DEM) and 3D point clouds. These outputs can be utilised to monitor vegetation, geothermal surface features, surface subsidence, and land use changes adjacent to geothermal areas (Harvey et al., 2016).

Here we compare point clouds collected 22 months apart at Crown Rd, Taupo, New Zealand (**Figure 1** and **Figure 2**), a known area of ground subsidence (Bromley et al., 2009). The point clouds are derived from UAS (December 2018) and crewed aircraft (February 2017). The purpose is to determine if subsidence at Crown Rd is ongoing and can be detected by the method.

In addition to the above photogrammetry method, we investigate the use of Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) to detect subsidence at Crown Rd, and at other subsidence bowls in the surrounding Taupo area previously identified by ground-based levelling surveys (**Figure 1**). PSInSAR is a remote sensing method that uses reflected satellite radar signals to accurately measure ground displacement. The PSInSAR method relies upon a "stack" of satellite images collected over time, to identify persistent scatterers (PS). PS are surface objects that reflect radar, including roof tops, bridges, dams, steam pipelines, antennae, large rock outcrops, and other prominent natural features. Using this method, the motion of each PS structure can be very precisely measured, and ground deformation can be determined. PSInSAR is more accurate than standard 2-pass interferometry, which compares only two satellite images. **Table 1** provides a comparison of subsidence detection methods capable of detecting subtle (mm/year) vertical change.

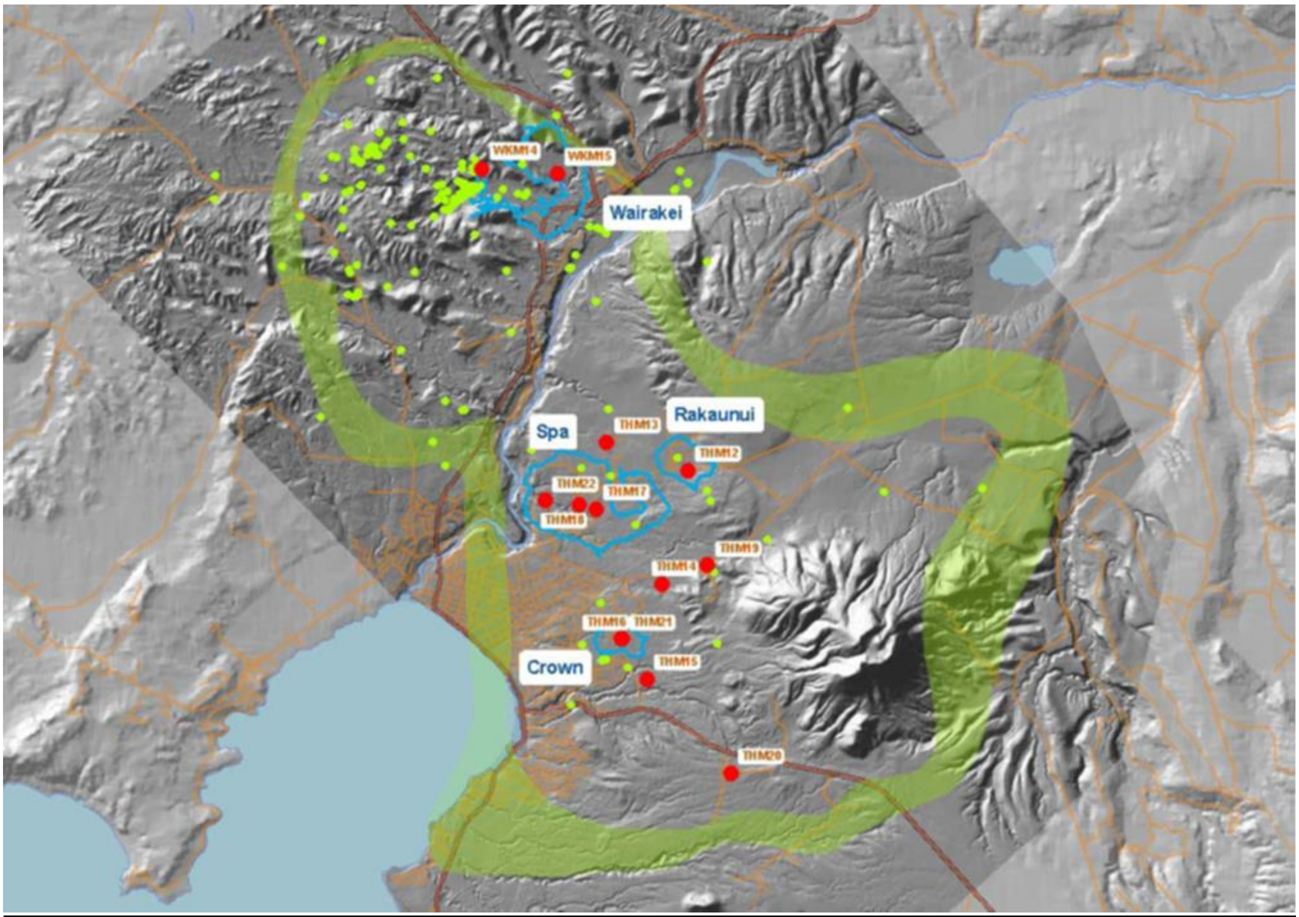

Figure 1 Map of the Wairakei-Tauhara Geothermal System. The resistivity boundary is shown by the green band. The four known subsidence bowls (identified with levelling surveys) are named and outlined in blue (figure from Brockbank et al., 2011).

Table 1 Comparison of Subsidence Detection Methods

Method	Advantages	Disadvantages
Levelling Survey (benchmarks)	- Established method	- Time and Cost - Low spatial resolution - Cannot measure vegetation
Photogrammetry	- Unlimited resolution - Can measure volumetric change in anything (surface, vegetation, construction)	- Spatial coverage limited to area flown (UAS or crewed aircraft) - Cost: Requires repeat flights
Sentinel-1 PSInSAR	- Global coverage (2015 – current) - Free data - Higher PS density in urban and unvegetated areas	- Requires multiple satellite images collected over time - Lower or zero PS density in heavily vegetated areas

2. METHODOLOGY

UAS (December 2018)

Imagery was collected at Crown Rd, Crown Park Reserve and Broadlands Rd Reserve (**Figure 2**), using a Canon S100 camera mounted to DJI Matrice 100 UAS (**Figure 3**)

20 ground control points (GCP) were collected with a Sokkia GRX2 global positioning system (GPS) Base Rover Receiver Kit paired with a Continuously Operating Reference Station (CORS) for Real-time kinematic (RTK) corrections. GCP included road markings and other easily identifiable features such as water drains. The vertical and horizontal accuracy of the RTK GPS was about 1 - 2 cm (as indicated by the GRX2 interface in the field).

Images were processed to a 3D point-cloud using Agisoft Photoscan. Coverage of the survey was 4.9 km^2, with a ground sampling distance (GSD) size of ~4 cm. Two GCP were reserved for error checking and indicate a positional root mean square error (RMSE) of 9 cm (XY) and 16 cm (Z).

Crewed Aircraft (February 2017)

Visible imagery was captured at Crown Rd, Crown Park Reserve and Broadlands Rd Reserve as part of crewed aircraft surveying (February 2017) (**Figure 2**). Imagery was collected using a large format Vexcel UltraCam mounted to a crewed aircraft. Images were processed to a 3D point-cloud using Agisoft Photoscan. Coverage of the survey was 7.5 km2, with a pixel size of ~7 cm.

8 of the GCP collected in 2018 were used to georeference the older crewed aircraft imagery. This approach is not ideal, but there was no better option because GCP were not measured in 2017. However, the 8 GCP were chosen outside of the Crown Rd subsidence bowl area, to maximize the possibility that subsidence in this area could be detected. A 2016 levelling survey commissioned by Contact Energy showed subsidence rates at Crown Rd (up to 300 mm/year)(**Figure 4**) had increased from 2009 (65 mm/year) (Bromley et al., 2009). Ongoing subsidence of this magnitude should in theory be detected by surveys 22 months apart.

UAS and crewed aircraft dense point clouds were clipped to the Crown Rd subsidence bowl area, then compared using the M3C2 plugin within CloudCompare software, which provides elevation change relative to the earlier dataset (meters, positive or negative). The resulting difference point clouds were converted to raster difference maps and imported to GIS software (QGIS) for visualisation.

Satellite (June 2018 – July 2019)

PSInSAR analysis was conducted using open source software including Sentinel Application Platform (SNAP) and the Stanford Method for Persistent Scatterers (StaMPS).

In PS analysis, interferograms are formed between a single master image and a number of available ‘slaves’ acquired on different dates. The first step was download available Sentinel-1 images for the Taupo area covering the time interval of interest (June 2018 – July 2019). After download, the area of analysis (Taupo) was extracted from the satellite data using SNAP software. This reduced the size of data and decreased processing time.

The second step was to compute individual interferograms using SNAP, combining the single master image with the 30 slave images. The resulting ‘stack’ was input to StaMPS for PS analysis. StaMPS then outputs mean velocity for all PS in the area of analysis for the time interval of observation. Further details of the method are provided by Cian et al. (2019).

Figure 2 Dense point clouds from crewed aircraft survey 2017 (left), and from the 2018 UAS survey (right). Red square shows approximate location of Crown Rd subsidence bowl. Note: 8 of the GCP from December 2018 were used to georeference the 2017 crewed aircraft imagery.

Figure 3 DJI Matrice 100 quadcopter.

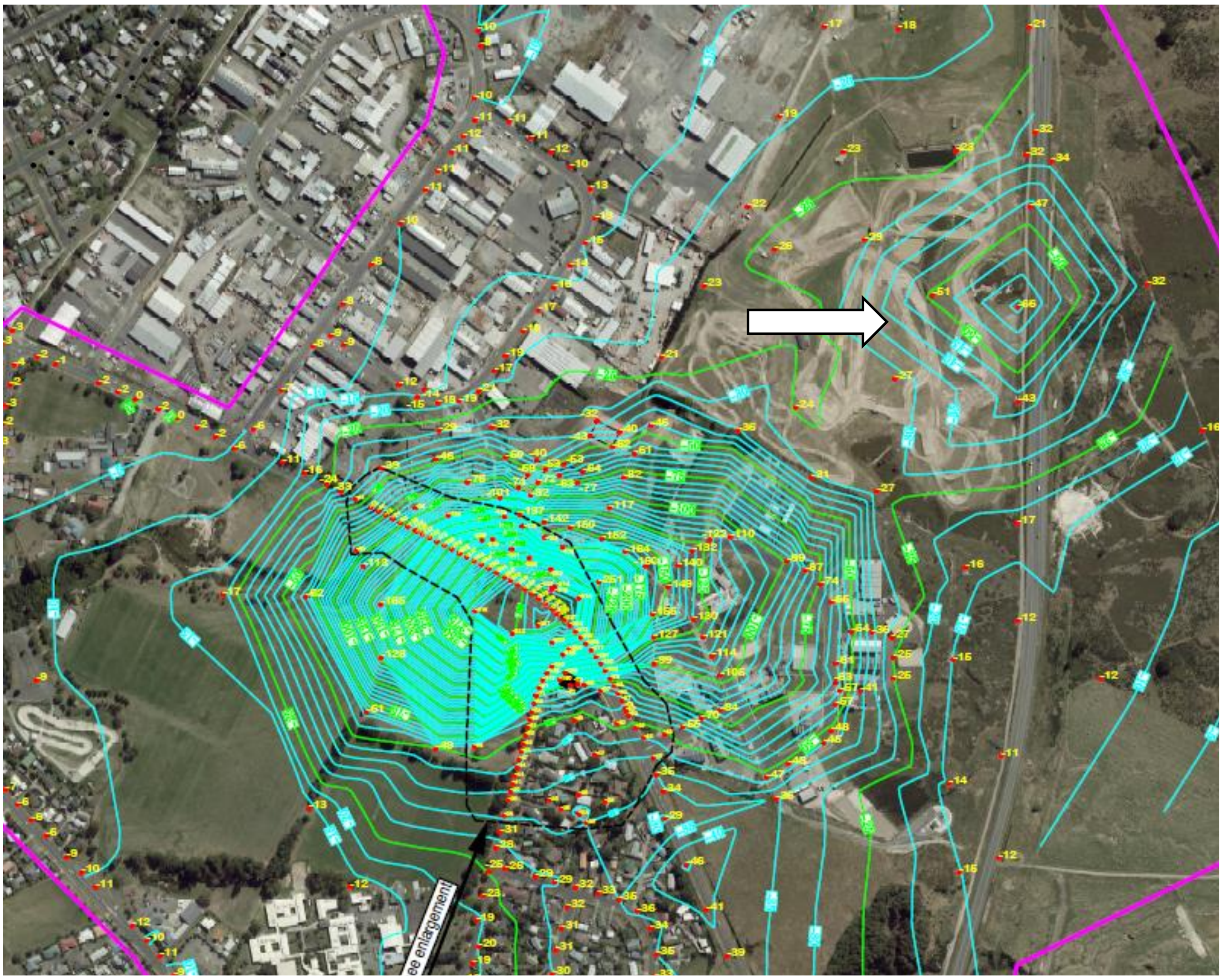

Figure 4 Crown Rd subsidence bowl contours from ground-based levelling survey data. Survey commissioned by Contact Energy and conducted 2015-2016. Large white arrow points to possible additional area of more subtle subsidence centred near the motocross park

3. RESULTS AND DISCUSSION

UAS and Crewed Aircraft

Comparison of UAS and crewed aircraft point clouds at the Crown Rd subsidence bowl clearly shows subsidence that corresponds with the ground-based levelling survey commissioned by Contact Energy (**Figure 5**). A possible additional area of subtle subsidence is centred near a motocross park (white arrow, **Figure 5***)*, which also agrees with levelling survey results (**Figure 4**). **Figure 6** shows more obvious surface change from new building and vegetation growth between February 2017 and December 2018. Similarly, **Figure 7** shows vegetation clearing over this period.

A possible area of more subtle subsidence is centred near the motocross park, which also agrees with levelling survey results. Difference maps showing construction of new buildings and vegetation growth (**Figure 6**), and vegetation clearing (**Figure 7**), are provided as a reality-check of the results; the difference maps clearly relate to surface change in the visible imagery.

Satellite

PSInSAR results at Crown Rd clearly shows subsidence that corresponds with both the ground-based levelling survey (Contact Energy, 2016)(**Figure 8**), and the crewed aircraft/UAS study (**Figure 9**). The maximum subsidence detected by PSInSAR is approximately 40 mm/year, which is slightly less than the ground-based levelling survey contours that pass through the same area (50 - 150mm/year)(**Figure 8**).

The subsidence continues to the northeast, through the motocross park (white arrow, **Figure 8**), toward the Crown Rd geothermal area, which agrees with levelling survey results (**Figure 4**).

Additional PSInSAR processing was undertaken at other known areas of subsidence associated with the Wairakei-Tauhara system (**Figure 1**) and showed agreement with previous levelling survey results (**Figure 10 and Figure 11).**

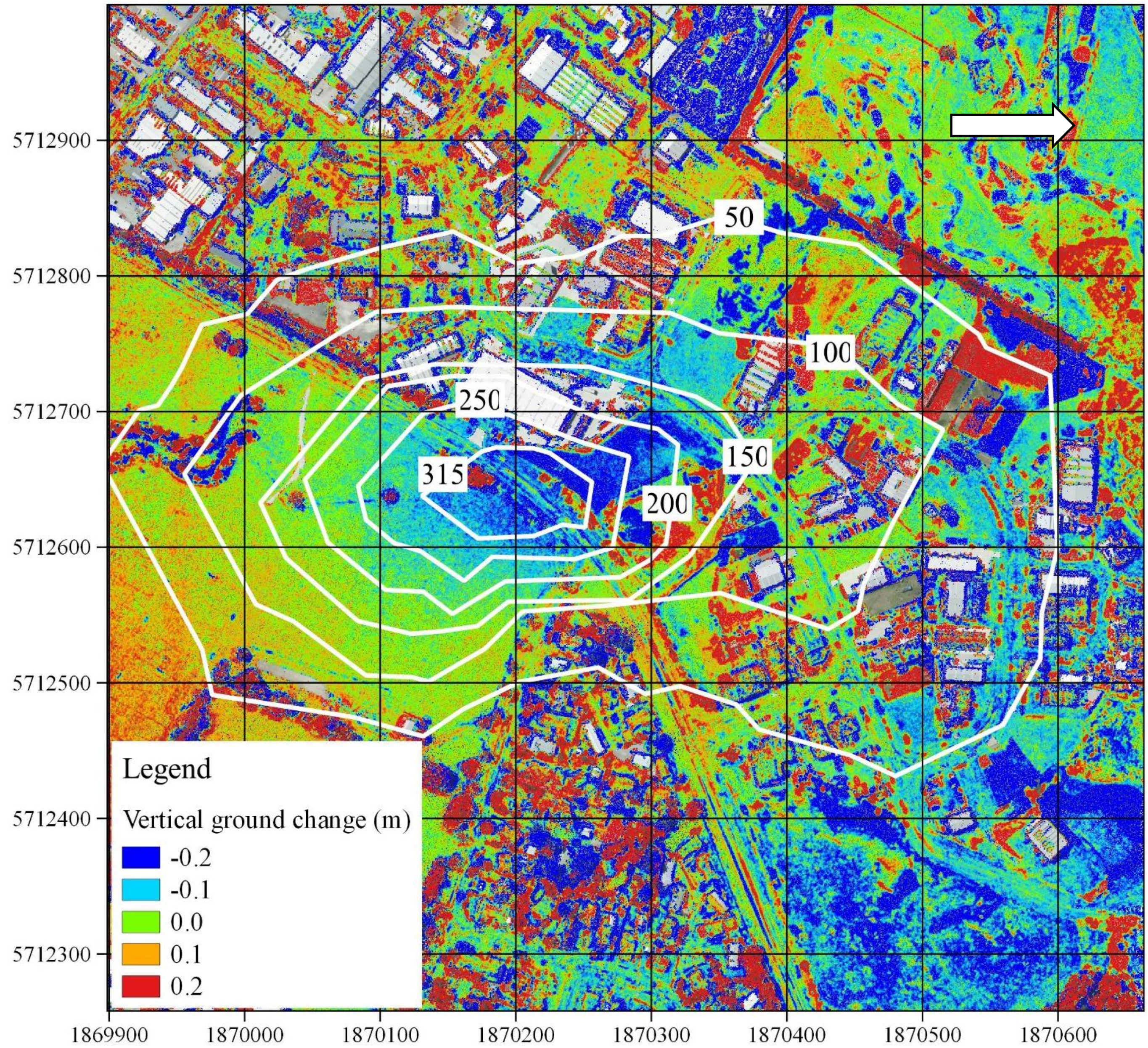

Figure 5 M3C2 ground difference map with levelling survey contours superimposed (labels have units of mm/year). Large white arrow points to possible additional area of more subtle subsidence centred near the motocross park, which also agrees with levelling survey results (Figure 4). Negative change in the southeast corner shows vegetation clearing (Figure 7). Note: contours digitized from Figure 4.

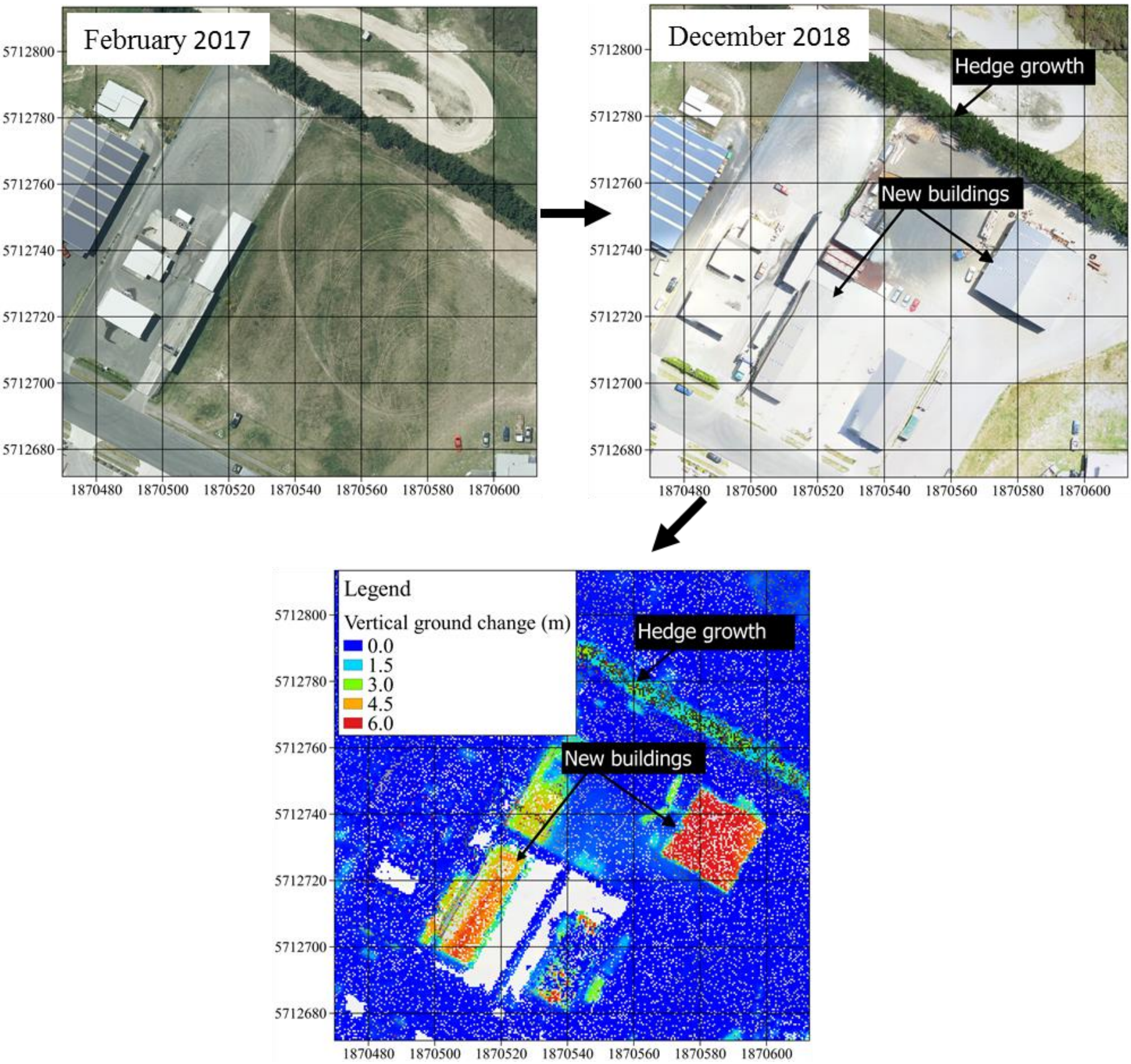

Figure 6 Before and after aerial photos, and M3C2 ground difference map showing construction of new buildings and vegetation growth between February 2017 and December 2018. Note: vertical ground change scale is from 0 - 6m, almost two orders of magnitude greater than in Figure 5.

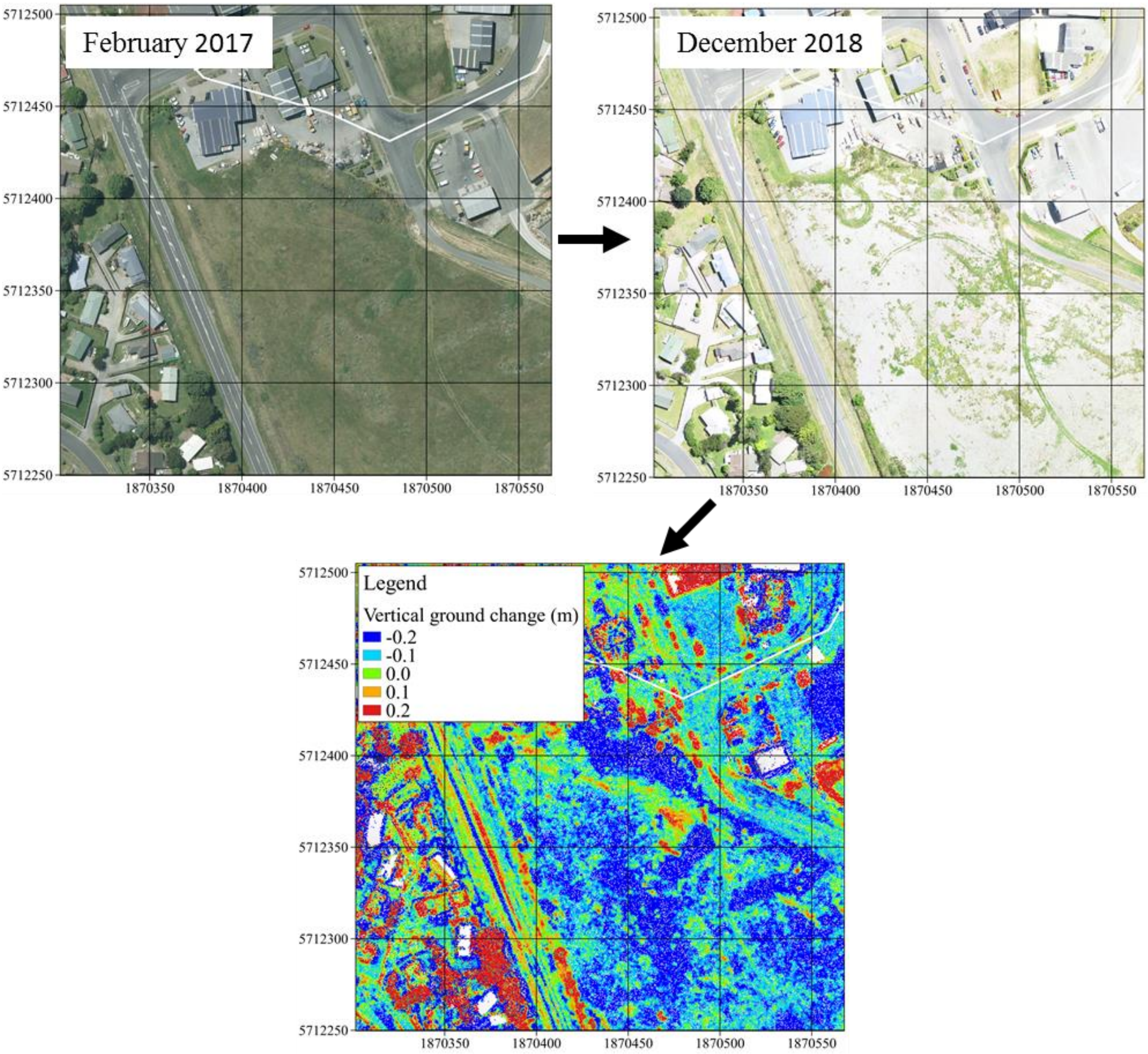

Figure 7 Before and after aerial photos, and M3C2 ground difference map showing vegetation clearing (southeast corner of Figure 5), between February 2017 and December 2018.

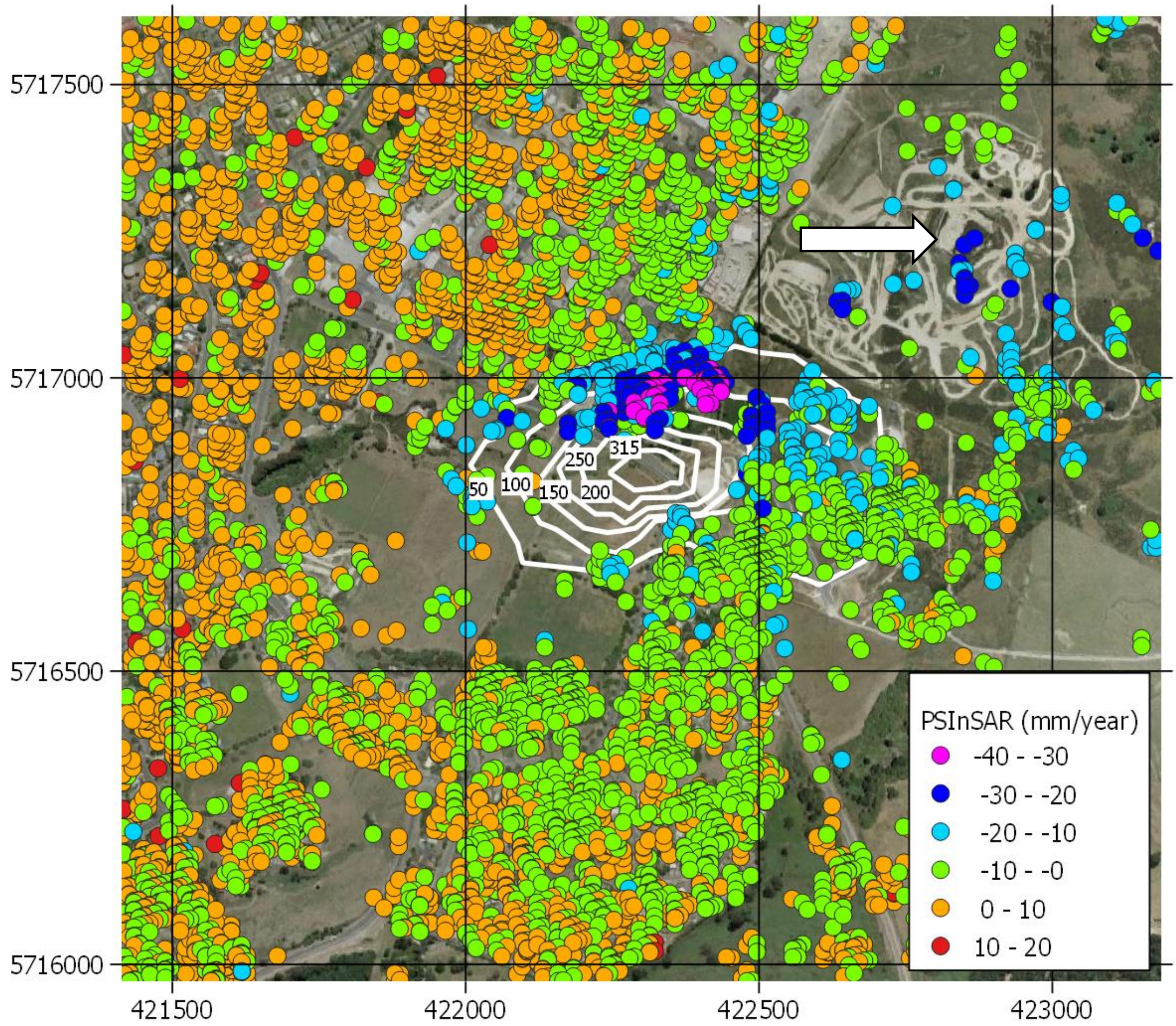

Figure 8 PSInSAR ground motion vertical velocities (2018-2019) overlaid upon Contact levelling survey contours (2015-2016). Note: Levelling contours (white box labels, units of mm/year) show same subsidence at the same location to PSInSAR. Large white arrow points to subsidence near the motocross park.

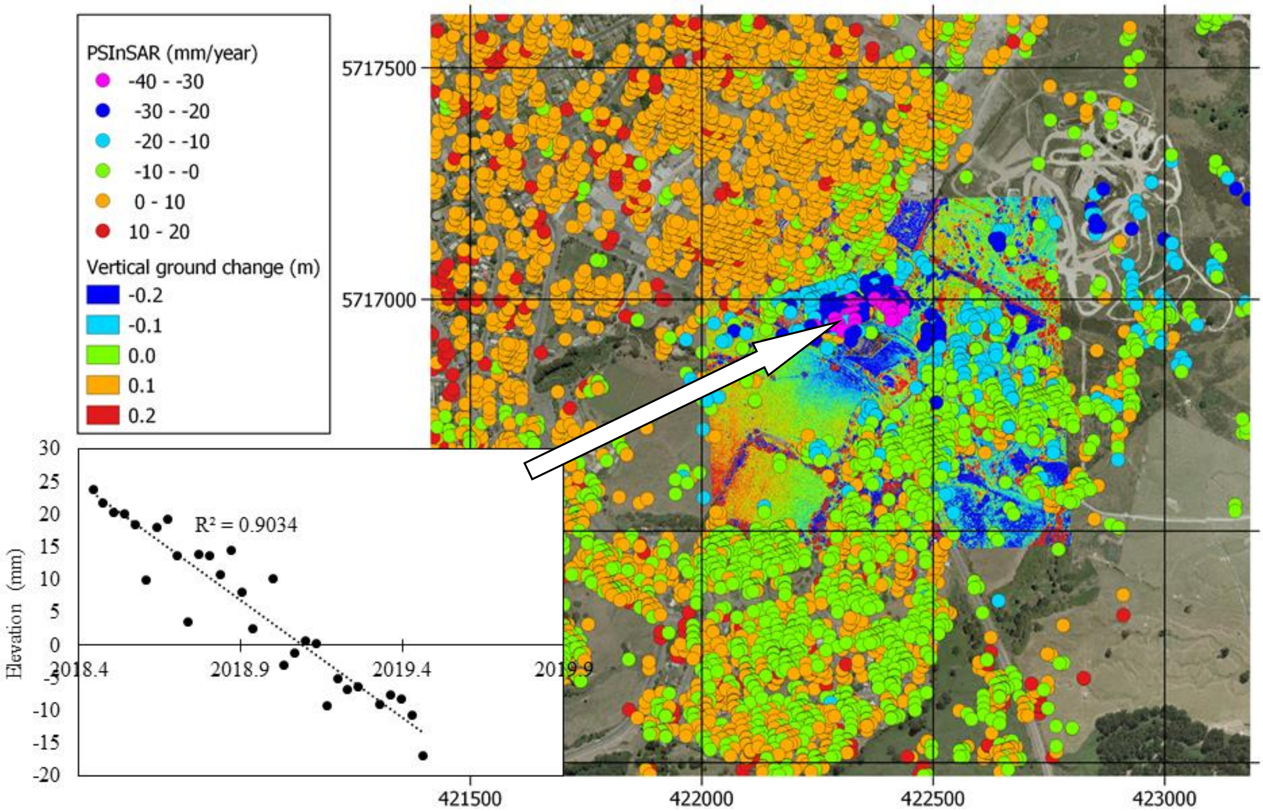

Figure 9 PSInsAR ground motion vertical velocities overlaid upon photogrammetry change detection results (Harvey Geoscience, 2019). Note: photogrammetry shows subsidence at the same location and with comparable subsidence rates to PSInSAR. Inset shows selected PS subsides at an approximately constant rate (35 mm/year) between 2018 - 2019 (white arrow points to the selected PS).

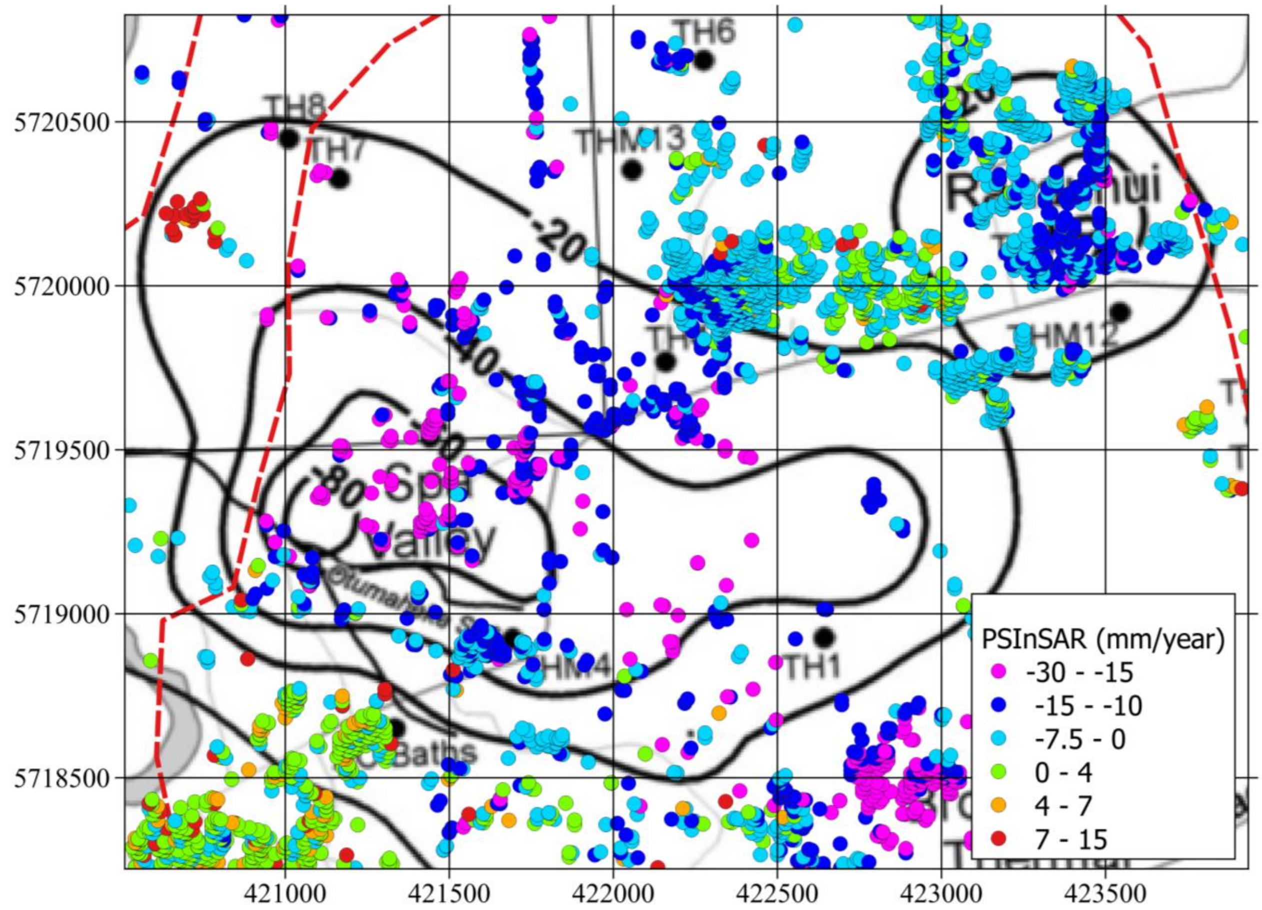

Figure 10 PSInsAR ground motion vertical velocities at Spa Valley and Rakaunui subsidence bowls (2018 – 2019) overlaid upon subsidence contours derived from levelling surveys (2001 – 2004 data; Bromley et al., 2009). Contours have units of mm/year.

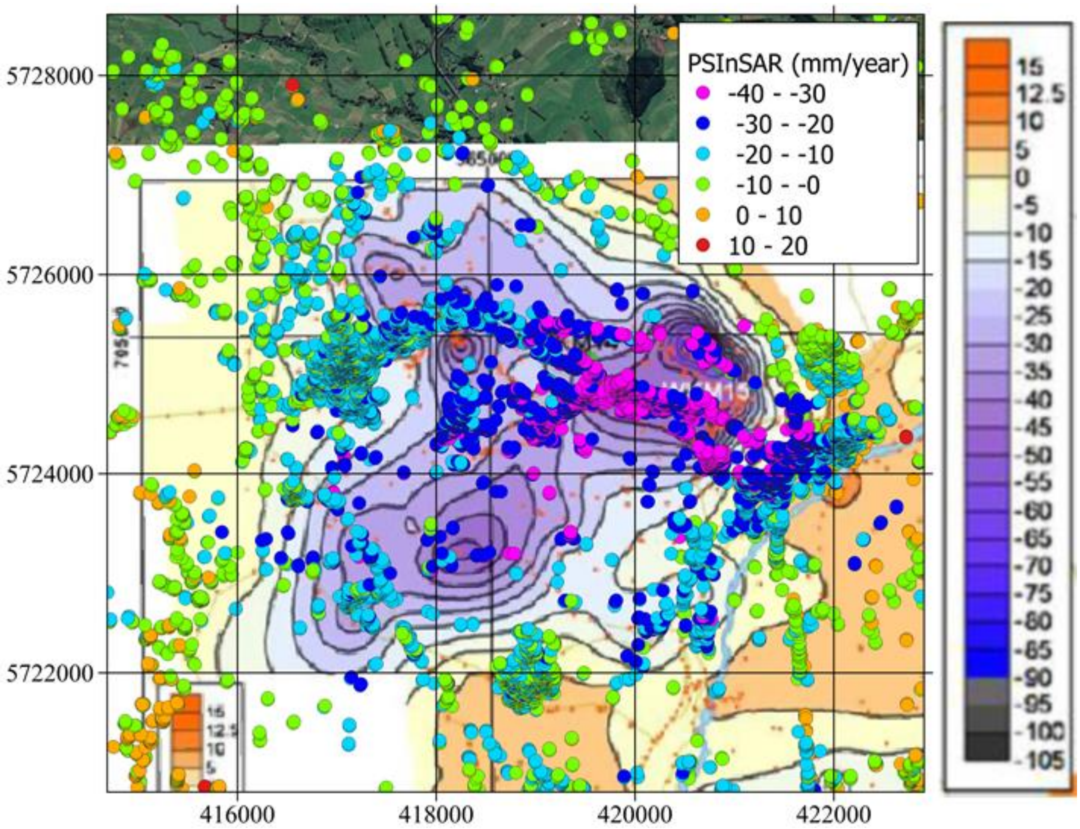

Figure 11 PSInsAR ground motion vertical velocities at Wairakei, Taupo (2018 – 2019), overlaid upon subsidence contours derived from levelling surveys (2004 – 2009 data; Bromley et al., 2015). Contours are 5 mm/year intervals, and coloured according to the scale on the right.

4. CONCLUSIONS

This study investigates the use of photogrammetry (crewed aircraft and UAS) and PSInSAR (satellite data) to quantify subsidence related to geothermal activity in Taupo, New Zealand. Photogrammetry derived point clouds were collected by aerial surveys conducted 22 months apart; UAS (December 2018) and crewed aircraft (February 2017). The resulting photogrammetry difference map shows a subsidence bowl in the same location as previously identified by ground-based levelling surveys. This provides evidence for continued subsidence at Crown Rd, and confidence in the photogrammetry method for monitoring subsidence and other types of environmental change.

PSInSAR results at Crown Rd clearly shows subsidence that corresponds with both the ground-based levelling survey (Contact Energy, 2016)(**Figure 8**), and the WRAPS/UAS study (Harvey Geoscience, 2019)(**Figure 9**). The maximum subsidence rate detected by PSInSAR at Crown Rd is approximately 35 mm/year, which is slightly less than ground-based levelling survey results (50 – 150 mm/year in the same location).

The lower maximum rate for the PSInSAR method (35 mm/year) may be because there were no PS at the centre of the subsidence bowl (mostly vegetated area), where the highest subsidence rates occur (**Figure 8**). However, a proportion of PS fall inside the 100 mm/year levelling survey contour, and the reason for this discrepancy is unknown. It is possible subsidence has slowed since the levelling survey in 2015-2016, however this seems unlikely given the long-term trend of increasing subsidence in the area (Bromley et al., 2009; Contact Energy, 2016). In July 2019 the centre of the Crown Rd bowl was closed to traffic due a sudden subsidence event that caused large cracks in the road, cutting water and wastewater to about 30 properties.

In addition to Crown Rd, PSInSAR analysis confirmed other known areas of subsidence in Taupo including Spa, and Rakaunui subsidence bowls (**Figure 10)** and Wairakei (**Figure 11**).

The PSInSAR method allows analysis of individual PS, showing the vertical position of a selected PS over time. This shows whether the rate of subsidence/inflation is constant or accelerating. A single PS analysed at the Crown Rd subsidence bowl shows an approximately constant rate of subsidence (35 mm/year) between June 2018 – July 2019 (**Figure 9** inset).

Our results show PSInSAR could be utilised to efficiently monitor vertical ground change over entire regions. The method has a wide range of applications of interest to geothermal development, including reservoir modelling, and monitoring vegetation, geothermal surface features, surface subsidence and inflation. More generally, potential applications include monitoring buildings and infrastructure, dams, mining, groundwater depletion and recharge, landslides, seismic and volcanic hazards. The photogrammetry method is more suited to smaller areas, but has important advantages including practically unlimited resolution, and the ability to detect and measure volumetric change in almost any surface (e.g. land surface, vegetation, construction).

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