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# Mapping and monitoring landslides in New Zealand using Sentinel-1 InSAR data: A case study from Gisborne

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## ABSTRACT

Landslides are widespread natural hazards that are responsible for substantial economic and societal damage globally each year. In New Zealand, landslides frequently occur on soil and rock, triggered by high rainfall, seismic activity, and land-use change and/or disturbance. This study focuses on the Gisborne district, an area particularly susceptible to landslide hazards because of the area's steep slopes, relatively young, soft geology, land-use change, extreme rainfall events and extra-tropical cyclones. However, the extent and rate of ongoing slope deformation in the Gisborne area is poorly known. Indeed, detecting ground deformation related to landslides is vital for identifying and managing areas at risk. Interferometric synthetic aperture radar (InSAR) is an active remote sensing imaging tool used to map and monitor surface deformation, with a cm to mm-scale of accuracy. Over the past decade, SAR systems have significantly developed and provide consistent, reliable, high-resolution global data. In particular, the launch of Sentinel-1 in 2014 marked a significant milestone, being the first civilian satellite designed explicitly for InSAR analysis, and it produces free and open access data. Advancements in InSAR processing software have also reduced the spatial, temporal, and atmospheric decorrelation, enhancing the precision of ground deformation measurements. In this study, we illustrate the potential of the multi-temporal (MT) InSAR technique called persistent scatter (PS) for detecting and monitoring ground deformation related to landslides in urban areas using Sentinel-1 data.

# 1. INTRODUCTION

Landslides are widespread natural hazards that are responsible for substantial economic and societal damage globally each year (Kjekstad & Highland, 2009). In New Zealand, landslides frequently occur on soil and rock, triggered by high rainfall, seismic activity, and land-use change and/or disturbance (Basher, 2013; Phillips et al., 2018). Indeed, since 1843 there have been at least 600-recorded fatalities related to landslide events in New Zealand, in comparison with 458 from earthquakes. The minimum damage costs associated with landslides are estimated to be between NZ $250-$300 million annually (Rosser et al., 2017). Further, with increasing urbanization, deforestation, land use-change, and climate shifts, the frequency of landslide events are expected to increase in the future (Gariano & Guzzetti, 2016). As a consequence, detecting ground deformation related to landslides will remain vital for identifying and managing areas at risk to help plan for future urban developments.

Landslide monitoring typically requires the continuous measurement of ground deformation, which is often done physically in the field. Although on-site visual measurements and in-situ sampling are extremely effective, it is often in remote and dangerous places and puts people and expensive equipment at risk. However, over the past two decades, remote sensing techniques such as Light Detection and Ranging (LiDAR) (Glenn et al., 2006), Unmanned Aerial Vehicle (UAV) surveys (Lucieer et al, 2014), and satellite-based Earth-observation such as optical imagery (Stumpf et al., 2017) and Interferometric Synthetic Aperture Radar (InSAR) (Béjar-Pizarro et al., 2017) have been used to map and monitor landslides to complement traditional on-site landslide observations and measurements. In particular, spaceborne SAR imaging systems provide a useful solution to many of these problems, because remote and dangerous sites can be surveyed without putting people or equipment at risk. Images can be taken in all weather conditions, allowing continuous coverage and hundreds of square kilometres can be analysed at a relatively low cost (Ciampalini et al., 2014). The ability of InSAR to measure and monitor surface deformation related to landslide events has been well documented (Hilley, 2004; Béjar-Pizarro et al., 2017; Bru et al., 2017; Ferretti et al., 2015). Today, InSAR is considered to be in the golden age of development (Moreira, 2013), due to the growing availability of global SAR data. There are currently 6 active spaceborne SAR missions that have satellites orbiting the planet and there are more than 10 decommissioned satellites with archive data available from 1991 (Moreira et al., 2013). The launch of Sentinel-1A in 2014 marked a significant milestone for InSAR development, being the first civilian satellite specifically designed for InSAR analysis and producing free open access data (Ferretti, 2014, p.151). Also, new and developing processing software makes the data available in easy and accessible formats. However, despite the rapid overseas take-up of this emergent space-borne technology, the application of InSAR for geotechnical purposes in New Zealand is still in its infancy.

This study focuses on applying persistent scatterer interferometry to map deformation related to landslides in Gisborne, an area particularly susceptible to landslide hazards because of the region's close proximity to an active plate boundary. The area encompasses steep slopes, relatively young, soft geology, deforestation, land-use change, and is susceptible to extreme rainfall events and extra-tropical cyclones (Phillips et al., 2018). However, landslides in Gisborne have not been mapped with any precision and the extent and ongoing deformation of landslide hazards in the urban area are poorly known.

## 1.1. InSAR

Interferometric synthetic aperture radar is an active remote sensing imaging tool used to map and monitor surface deformation, with a cm to mm-scale of accuracy (Hu et al., 2014). As the name suggests, InSAR is a combination of Synthetic Aperture RADAR and interferometry. Synthetic Aperture Radar imaging systems work by transmitting an electromagnetic microwave from a sensor mounted on an aircraft or satellite to the Earth’s surface and Interferometry exploits the phase difference between two or more SAR images (Ferretti, 2014, p.4). The standard InSAR technique for mapping ground movement is called differential InSAR (D-InSAR), which uses the repeat pass method to compare two or more SAR images, taken over the same area, but at different times (Ferretti, 2014, p.71). More advanced multi-temporal InSAR (MT-InSAR) techniques such as persistent scatterer (PS) (Ferretti et al., 2001; Ferretti, 2014, p. 73), small baseline (Berardino et al., 2002) and a combination of the two (Hooper, 2008), use a set of interferograms rather than just two images. This reduces the spatial, temporal, and atmospheric decorrelation, enhancing the precision of ground deformation measurements (Hu et al., 2014; Ferretti, 2014, p. 73). The type of method used depends on the data available, the study area and the information the user is trying to extract. The PS method uses a single SAR image, called the master, from which all interferograms are formed and uses radar targets considered coherent over time such as buildings for pixels (Ferretti, 2014, p. 73). For this reason, the PS method is better for urban environments that have more coherent targets. The SB technique works better in rural areas, as the approach uses pixels that are spatially coherent in the interferograms (Ferretti, 2014, p. 82). The SB method produces a network of interferograms that have short temporal intervals and spatial baselines in order to increase interferogram correlation, instead of having one master image (Hooper, 2008).

Deformation measurements are taken in the satellite's line of sight (LOS). The majority of SAR satellites have a near-polar orbit and a sensor with a right-looking geometry. This means the same area is imaged twice by the two different viewing geometries, because the satellite moves in a descending orbit, from the North Pole to the South Pole and in an ascending orbit, from south to north (Ferretti, 2014, p. 26). For landslide related deformation, the movement is primarily in the direction of maximum slope, which means the optimum direction for measuring movement is parallel to the slope (Béjar-Pizarro et al., 2017). This is why east-west deformation is more readily detectable than north-south deformation, although both ascending and descending orbits can be combined to extract the vertical and horizontal component (Ferretti, 2014, p. 81).

### 1.2. Sentinel-1

Sentinel-1 is the most recent satellite launched by the European Space Agency as part of the Copernicus initiative. Sentinel-1A archive data is available from June 2014 and has a revisit time of 12 days for certain areas. In 2016 Sentinel-1B was launched and joined Sentinel-1A on the same polar orbit, reducing the satellite revisit time to 6 days in Europe and other certain areas of interest (Torres et al., 2012). The revisit time for New Zealand is primarily 12 days. The primary imaging mode of Sentinel-1 is the Interferometric Wide (IW) swath mode, which has a swath width of 250 km, a look angle of 29-46º and a 14 m pixel resolution in the azimuth direction and 5 m in the range direction.

### 1.3. Aims

The proposed study aims to:

1. Apply persistent scatter interferometry to identify landslide related deformation in the Gisborne urban area.

2. Highlight the potential of free and open access SAR data and InSAR processing software as a fast, low cost reconnaissance tool for imaging and monitoring geotechnical hazards in New Zealand.

## 2. STUDY AREA

Gisborne city is located on the Raukumara Peninsula on the east coast of New Zealand’s North Island (Fig. 1a). The city is primarily built upon the Poverty Bay Flats, a low-lying alluvial flood plain of the Waipaoa River, which extends to the west of the city. Surrounding the plains are steep hills that do not exceed 800 m above sea level and display a terracette (stepped) morphology. Gisborne has one of the highest erosion rates in New Zealand, driven by steep slopes, easily erodible material, high rainfall, recent extensive deforestation and large numbers of grazing animals (Basher, 2013). The most common type of landslide in Gisborne are flows and slides in shallow soils that are triggered by heavy rainfall, similar to other regions across New Zealand (Phillips et al., 2018). Previous records show several slope instability events occurring across the steep slopes within the urban area and along riverbanks and terraces (Fig. 1b).

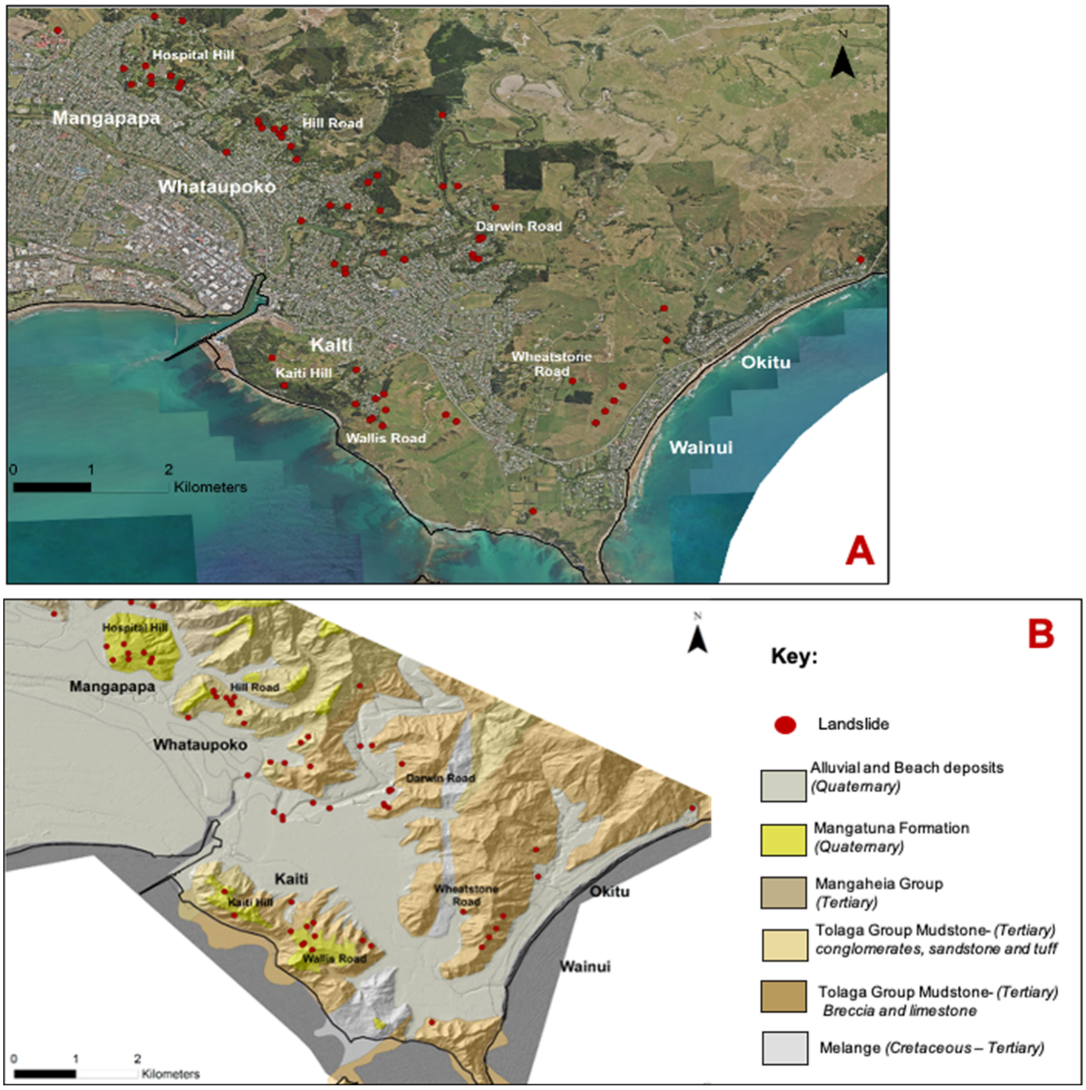


*Figure 1: a) Aerial image of Gisborne city showing the distribution of known landslide events. b) Distribution of recorded landslides across Gisborne city and their relationship with different lithological formations and units.*

## 3. METHODS

For this study, we applied the persistent scatterer interferometry technique to identify landslide related deformation within the urban area. The PS method was selected because it uses radar targets considered coherent over time, such as buildings and can provide dense pixel coverage in urbanized areas. The stack of SAR images were processed using ISCE (Rosen et al., 2012) and displacement and timeseries were obtained using StaMPS (Hooper et al., 2012). In StaMPS, the PS method uses a single SAR image, called the master, from which all interferograms are formed. Then finally, atmospheric corrections were applied using Phase-based linear tropospheric corrections with TRAIN (Bekaert et al., 2015).

### 3.1. Data and Processing

For this study, we used 59 descending Sentinel-1 IW swath images from October 2014 to December 2017 (Table 1) for processing.

*Table 1: Details of the Sentinel-1 data used in the InSAR analysis.*

| Satellite | Orbit Direction | Image dates | No. of SAR Images | Track No. | Sub-Swath Processed |
|---|---|---|---|---|---|
| S1A | Descending | 2014/10/17-2017/12/24 | 59 | 175 | 1 |

For the PS scatter processing, the image acquired on the 6th of October 2016 was used as the master image and 45 interferograms were processed. The master image was selected from roughly the centre of the data set, to reduce temporal decorrelation, and also at the time of acquisition there was no precipitation to help reduce the effects of atmospheric decorrelation. All measurements were taken in respect to a stable reference point in the centre of Gisborne (Ministry of Justice building, 178.0278 -38.6687), an area assumed to be non-deforming.

## 4. RESULTS AND DISCUSSION

The results from the PS interferometry are displayed in Figure 2. Each point represents the average velocity (mm/year) in the line of sight (LOS) direction, with positive values being towards the satellite and negative moving away. The measurements indicate average ground displacements of –6 to 6 mm/year in the LOS (Fig, 2). A high density of PS pixels can be seen in the centre of the city and along the eastern coast, but few are observed in the less urbanized areas in the southeast and on the northern fringes of the developed areas (Fig. 2). Two sites with known landslide events have been highlighted in Figure 2 to display their PS results.

The first site is located in Okitu on the eastern coast (Fig. 3a), where several houses are built upon slopes with a history of failure. Several of the houses have PS pixels and indicate movement away from the satellite towards the coast. Figure 3b shows a time series plot that displays the relative deformation (mm) of the point highlighted in Figure 3a. The time series plot indicates the PS is moving away from the satellite, having moved 10 mm towards the coast between 2014 - 2017.

The second site is a typical example of a landslide in Gisborne (Figure 4a). Located near Kaiti Hill at Titirangi Drive and Wallis Road (Fig. 4a), where there is a large ongoing complex landslide (Davies & Cave, 2017). Slope failure at the site was first recognized in 2014 and stability rapidly deteriorated in 2015, which resorted in a house being demolished by authorities (Davies & Cave, 2017). In the winter of 2017, heavy rainfall triggered the reactivation of the landslide (Fig. 4a), where it transitioned from a rotational slump to a debris flow (Davies & Cave, 2017). In the time series plot in Figure 4b, the deformation between May-August 2017 shows movement away from the satellite downslope towards the ocean. This is consistent with the reactivation event recorded in the winter of 2017 (Davies & Cave, 2017). The plot also indicates that deformation began in the summer of 2017 months before the reactivation of the landslide (Fig 4b). The houses are still at risk from slope failure and future ground movements are inevitable if the ground is not stabilised.

The two sites show the potential of InSAR as a reconnaissance tool for detecting ground deformation related to landslide events. However, the PS technique did not detect phase-coherent pixels in non-urbanized and

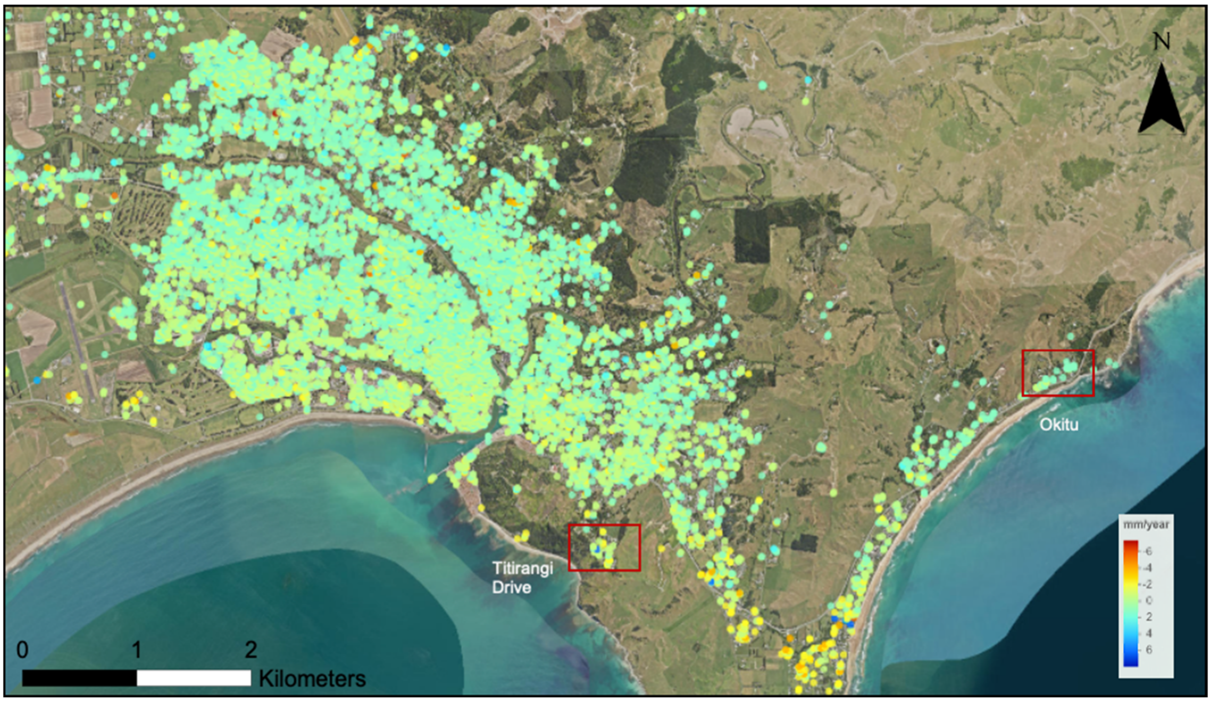


*Figure 2: Distribution of the PS results in Gisborne. A high density of scatterers can be seen in the urban area. Two areas of interest have been outlined in the red boxes, Titirangi Drive and Okitu. Plotted using the StaMPS-Visualizer App by Höser (2018).*

highly vegetated areas and the deformation in this analysis is only measured in the direction of LOS, which makes it difficult to detect north-south movement. To overcome these challenges, further analysis of the study will be made using the small baseline technique to try and detect scatterers in rural areas and use data from both descending and ascending orbits, to extract vertical deformation. The vertical deformation is required to reliably extract seasonal deformation related to the shrink-swell movement of clays and also infer building deformation.

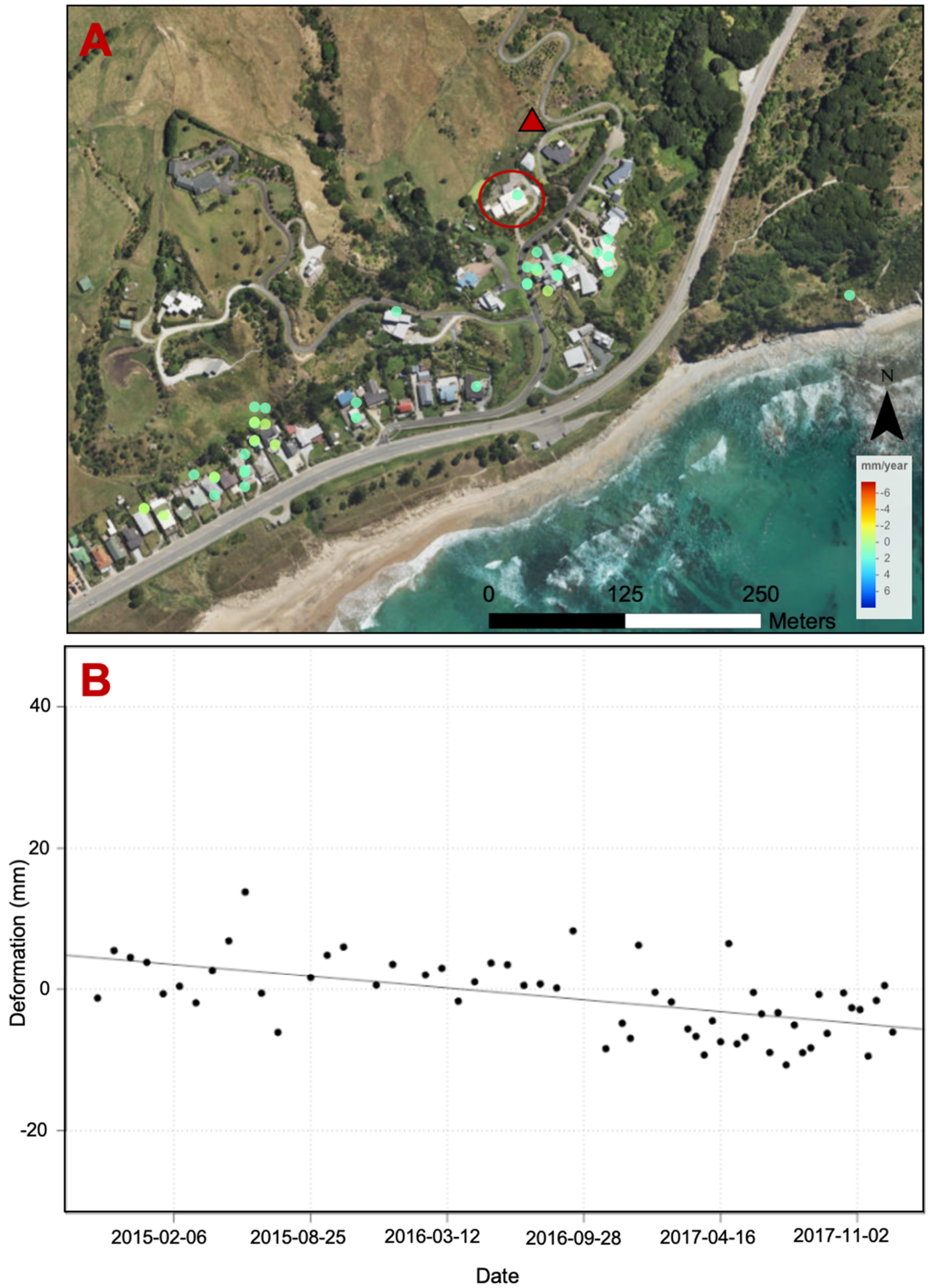


*Figure 3: a) Map showing the PS distribution on the east coast in Okitu. The red triangle shows a previously recorded landslide location, and the PS inside the red circle was used for the time series plot. b) Time series plot of the PS, showing continuous deformation away from the satellite. Plotted using the StaMPS-Visualizer App by Höser (2018).*

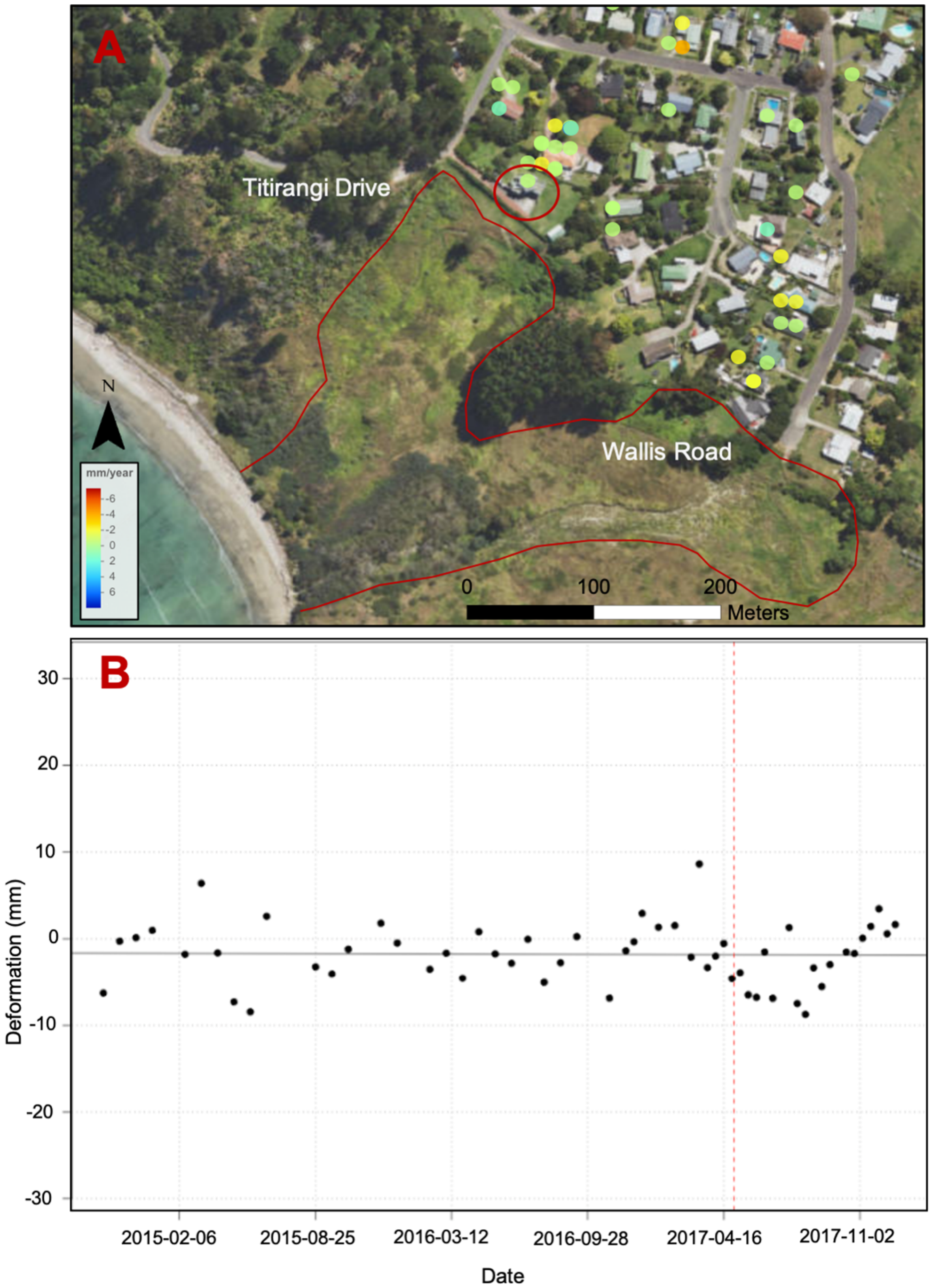


*Figure 4: a) Map showing the PS distribution of Titirangi Drive and Wallis Road. The extent of the active landslide has been outlined in red based on the report by Davies & Cave (2017). The PS inside the red circle was used for the time series plot. b) Time series plot of the PS on Titirangi Drive, showing deformation downslope away from the satellite during the reactivation event in May-July 2017, which is represented by the dashed red line. Plotted using the StaMPS-Visualizer App by Höser (2018).*

## 5. CONCLUSION

Our study highlights the potential of using free open access Sentinel-1 data as a reconnaissance tool to detect ground deformation related to landslides. The two study sites in Gisborne demonstrate how the PS technique can be used to monitor ongoing slope movement in urban environments and examine how deformation has changed over time. The technique can be applied to assist conventional ground measurement methods in long term monitoring projects for detecting ground deformation. Although site conditions must be taken into consideration when undertaking InSAR analysis. The technique is less reliable in highly vegetated areas and spatial, temporal and atmospheric decorrelation are factors that can limit the accuracy of results. However, our results are the first undertaken in Gisborne and produced using free and open access data and software. Further analysis will be undertaken to improve the results such as using the small baseline technique and including both ascending and descending data to extract the vertical deformation. Indeed, higher resolution SAR data can be used to try and increase the number of scatterers but at a higher cost. Over the past decade, SAR systems have significantly developed and can provide consistent, reliable, high-resolution global data. The development of InSAR is encouraging. In 2022 the first SAR satellite with dual frequency radar, with both L-band and S-band systems available, called NISAR will launch (Chapman et al., 2019). The mission is a collaboration between NASA and ISRO and the data will be free and open. The continued technological advancement of SAR systems means continuous and reliable global monitoring system, with high resolution, wide swath images can be achieved in the future for real time hazard assessments, disaster management and geotechnical monitoring.

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