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Development and testing of a method to monitor peatland subsidence in the Waikato Region

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Prepared for: Waikato Regional Council

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Summary

Project and Client

- Waikato Regional Council (WRC) require robust spatial information on regional peatland subsidence rates and spatial variation for state of the environment monitoring, to support implementation of the Waikato Regional Policy Statement (WRPS) and to inform long-term planning.
- WRC have contracted Manaaki Whenua – Landcare Research (in collaboration with the University of Waikato) to develop a new Waikato regional peat subsidence monitoring network for drained peatlands under agriculture.
- This document reports on the method development phase of the project. The purpose was to ensure the suitability of the methods selected during the previous phase of the project for monitoring peatland subsidence at 5-yearly intervals.

Objectives

- Determining accuracy and repeatability of the surface real time kinematic (RTK) global navigation satellite system (GNSS) survey approach.
- Determining accuracy and repeatability of airborne LiDAR including comparison with ground check point data to quantify uncertainty associated with variation in surface vegetation.
- Preliminary evaluation of the magnitude of intra-annual peat surface oscillation (PSO) and its influence on permanent subsidence detection at 5-yearly monitoring intervals.
- Evaluate the potential to use historic Daveron (1978) peat depth data to provide early information on differences in subsidence rates between land uses.

Evaluation of GNSS surface survey

- The accuracy of the Leica GS15 RTK GNSS system was tested by repeated measurements of location and height over Land Information New Zealand (LINZ) geodetic markers using both the LINZ and Global Survey SmartFix networks of continuously operating reference stations (CORS).
- Accuracy varied between available CORS at anyone location ranging from 0.001 ± 0.009 m (standard deviation, SD) to –0.088 ± 0.015 m (SD) of the geodetic marker height averaged over 5–10 measured heights repeated at 4 different points in time.
- The standard deviation over the geodetic markers were similar (0.009 – 0.015 m) between CORS resulting in a 95% confidence interval that ranged between ±0.003 and 0.007 m of the measured height. This suggests precision was very similar between CORS and absolute differences in height were a consistent offset, as opposed to random uncertainty, and therefore can be corrected for.
- Evaluation suggests vertical accuracy of RTK GNSS is in the order of ±0.01 m when 5–10 measurements are taken over a geodetic marker of known height. Precision is also likely within ±0.01 m when averaged over 25 points/m^2.

Evaluation of airborne LiDAR

- LiDAR was acquired with a Riegl VUX-1LR system from an EC120 helicopter over Moanatuatua and Motukaraka peatlands under optimal weather conditions in June 2019.
- LiDAR data were processed, calibrated, and classified using standard routines into ground returns, above ground returns and noise. The average density of classified ground returns was 49 points/m^2 at Moanatuatua and 33.5 points/m^2 at Motukaraka.
- Mean differences between airborne LiDAR (ground points) and ground-based check point data (RTK GNSS) were 0.001 m ±0.04 m (SD) at Moanatuatua and –0.003 m ±0.072 m (SD) at Motukaraka. However, differences were influenced by vegetation cover and were smallest for short grass of 0.013 m ±0.036 (SD) but up to 0.107 m ±0.048 (SD) for tall (0.3 – 0.4 m) broadleaf vegetation (Plantain) representing a worst-case scenario.
- For LiDAR flown at a point density of 45–50 points/m^2 it is likely the change detection threshold will be on average about 0.05 – 0.06 m and therefore suitable for measuring expected change of 0.1 m over 5-year monitoring intervals.

Evaluation of historic Daveron peat depth data

- A subset of 25 historic peat depth points were interpolated from the Daveron (1978) contour maps and remeasured to determine if these historic data could be used to provide early information on differences in subsidence rates between land uses.
- A good relationship (r^2 = 0.85) between the predicted depth in 1976 and the depth measured in 2019 indicated the historic data have potential to provide early information.
- Evaluation of the importance of going back to the exact location of a historic point compared to anywhere on the surface indicated there is little additional statistical power in returning to the historic point locations.
- From a statistical scenario based on measured variation in the collected data a mean difference in subsidence rates of about 0.02 m per year would be needed to detect a significant difference in subsidence rates between land uses over the 43-year period.

Peat surface oscillation

- The surface of natural peatlands can oscillate seasonally because of changes in water-table (Fritz et al. 2008) and depending on its magnitude in drained peatlands, surface oscillation has potential to confound shorter term (e.g. 5-yearly) re-survey intervals.
- During the method testing phase, peat surface height was monitored on two farms at Moanatuatua using repeat surface survey (RTK GPS) across transects at a frequency of about once per month and using paired pressure transducers to measure change continuously.
- Surface oscillations of between 0.04 m and 0.06 m occurred between January and August 2019. This monitoring is ongoing.
- The magnitude of measured PSO over this short period is about half the expected subsidence over a 5-year monitoring interval and is thus a risk to detection that is difficult to quantify.
- We suggest peat subsidence monitoring is done late winter/early spring to ensure the peatlands are at their wettest and PSO research is continued.

Recommendations

- Surface survey using RTK GNSS is suitable for detecting expected surface height changes of 0.1 m over a 5-year monitoring interval with a change detection threshold of 0.025 – 0.03 m. We recommend capturing 25 points/m^2 to characterise the patch as opposed to a point.
- Airborne LiDAR is suitable for detecting change in peat surface height at 5-year monitoring intervals but uncertainty increases with pasture length. We recommend the regional network is flown to achieve a ground return density of 45–50 points/m^2. This should provide a change detection threshold for pasture vegetation up to 0.2 m tall of 0.05 – 0.06 m, which is well within the expected surface change of 0.1 m over 5 years. However, detecting differences in subsidence rates between land uses and management practices may not be possible over a 5-year monitoring period. We also recommend monitoring is done in late winter when pasture covers are generally low to minimise the potential for pasture covers to prevent change detection.
- Comparing current peat depths to that interpolated from historic Davoren (1978) contour maps may detect a difference in subsidence rates between land uses, if a mean difference of 0.02 m per year occurred over the 43-year time period. Little additional statistical power is gained by returning to historic point locations and we recommend using the surface as opposed to the points to avoid constraining network design based on historic data.
- Evidence collected to date indicates seasonal PSO is of a similar order of magnitude to expected change over a 5-year monitoring period. Currently, PSO is a risk to detection that is difficult to quantify, and further research is required to better understand its magnitude, drivers, and spatial variation. We suggest monitoring is done in late winter/early spring to ensure the peatlands are at their wettest and research into PSO is continued.

1 Background

The Waikato Region has about 100,600 ha[1] of peatlands, of which about 81,500 ha[2] has been drained, mostly for agriculture, resulting in shrinkage, consolidation, and oxidation of the Organic Soil. These three processes are collectively called peat subsidence, which is a gradual lowering of the land surface. The ongoing drainage–subsidence cycle results in an increased risk of flooding, prolonged high soil moisture, reduced wetland sustainability, reduction in drainage capacity, a requirement to prematurely upgrade, repair or install drainage and other infrastructure, and carbon emissions. Subsidence rates are spatially and temporarily variable, dependent on factors including time since drainage, land use, land and drainage management, and peat type. In the Waikato region, recent work has reported an average peat subsidence rate of about 0.02 m y^{-1} (Pronger et al. 2014).

Waikato Regional Council (WRC) require robust spatial information on regional peatland subsidence rates and spatial variation for state of the environment monitoring, to support implementation of the Waikato Regional Policy Statement (WRPS) and to inform long-term planning. WRC have contracted Manaaki Whenua – Landcare Research (in collaboration with the University of Waikato) to develop a new Waikato regional peat subsidence monitoring network for peatlands under agriculture. A previous technical report (Pronger et al. 2019) summarised the advantages and limitations of a range of measurement methods that could be used to monitor peatland subsidence across the Waikato region in addition to the limitations of spatial layers available to inform network design. Here we document the method development phase. This includes testing of airborne light detection and ranging (LiDAR) and global navigation satellite system (GNSS) surface survey. We also examine the value and limitations of integrating historic peat depth data and provide evidence for the occurrence and the magnitude of seasonal peat surface oscillation (PSO).

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[1] This area estimate is based on the extent of Organic Soils within the Waikato Regional Council boundaries estimated from the combination of S-map where complete and the Fundamental Soils Layer where S-map data was not available and was correct at the time of writing. However, since this report was written area estimates for Organic Soils have changed based more recent soil mapping. Frequent soil map updates occurred throughout the project.

[2] This area estimate is calculated from the area of drained land uses identified in LCDB v4.1, which includes high and low producing exotic grassland, cropland, orchards, forestry and urban land, on Organic Soils. This area was correct at the time of writing. However, since this report was written area estimates for Organic Soils have changed based more recent soil mapping and landcover may have changed.

2 Objectives

The purpose of the method development phase was to ensure the suitability of the proposed methods for monitoring peatland subsidence at 5-yearly intervals in the Waikato region. Objectives included:

- Determining accuracy and repeatability of the surface real time kinematic (RTK) GNSS survey approach.
- Determining accuracy and repeatability of airborne LiDAR including comparison to ground check point data to quantify uncertainty associated with variation in surface vegetation.
- Preliminary evaluation of the magnitude of intra-annual peat surface oscillation and its influence on permanent subsidence detection at 5-yearly monitoring intervals.
- Evaluating the potential for historic data to provide early information on differences in subsidence rates between land uses.

3 Study sites

In consultation with WRC, Moanatuatua (Fig. 1, red circle) was chosen as a suitable location to carry out the method development phase of the project, because it was close to both Hamilton and the airport, included a range of land uses and surface covers, and aligned research was being done there. However, the opportunity arose to include Motukaraka (Fig. 1, blue circle) in the LiDAR testing phase because LiDAR was being flown there as part of a level of service review by WRC Integrated Catchment Management (ICM).

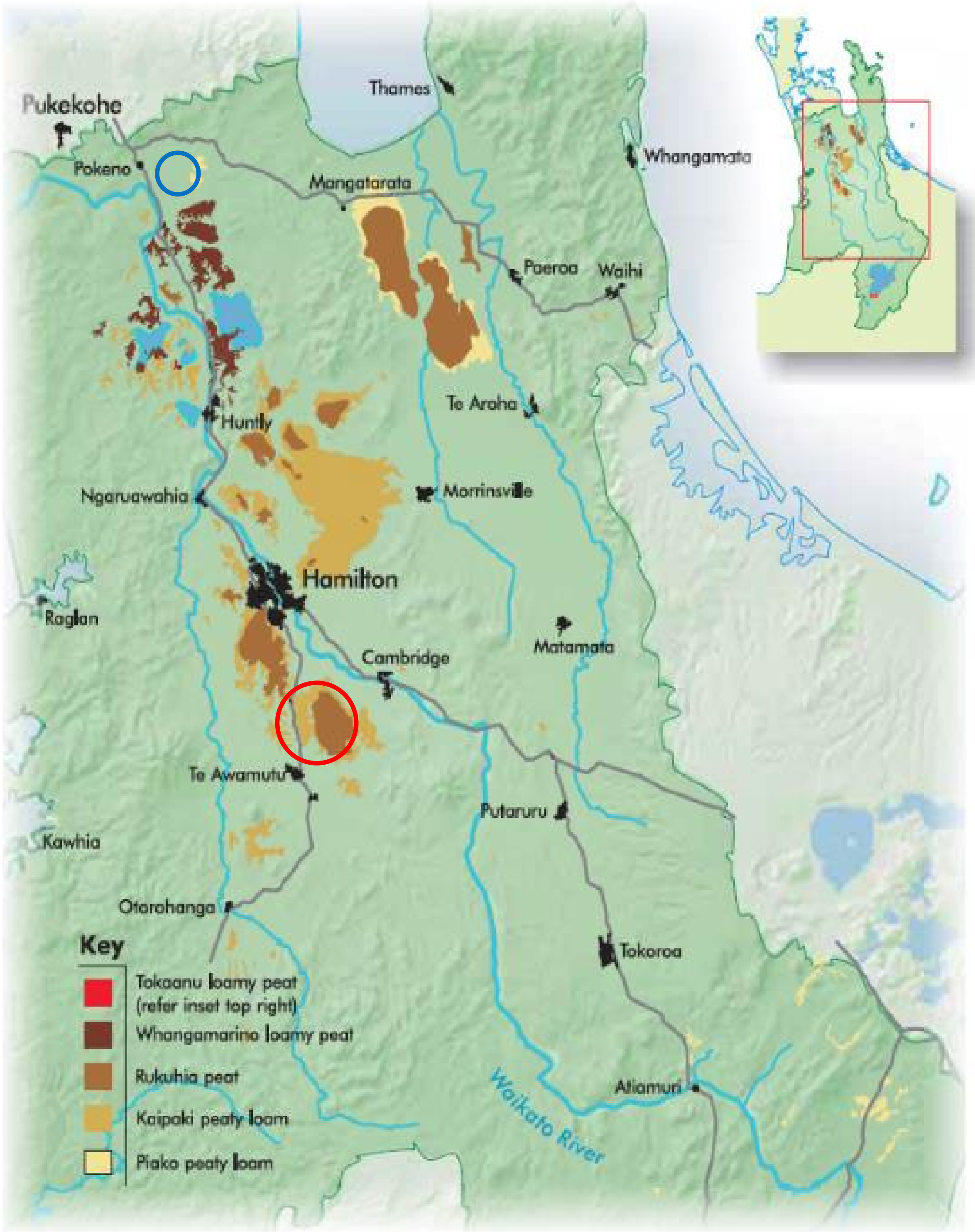

Figure 1. Location of method development sites in the Waikato Region, showing Moanatuatua south of Hamilton (red circle) and Motukaraka east of Pokeno (blue circle).

4 Evaluation of GNSS surface survey

Point-based surface survey measurements are required to ground truth helicopter-based LiDAR and to provide reference surface heights for future ground-based subsidence monitoring.

4.1 Method selection

In the review of methods component of this work (Pronger et al. 2019) point-based GNSS surface survey was chosen and it was indicated we would use the highest accuracy static approach as opposed to RTK and post processed kinematic (PPK) GNSS. However, the static approach takes about 1–2 hours to take a single high accuracy measurement. During field testing, it became apparent that capturing multiple points over the peat surface was more important than mm level accuracy. The value of a single high accuracy point is also questionable because on a grazed peat soil pugging is inevitable, especially during the wetter months, and this alone could result in a localised change in surface height in the order of 0.1 m. During the re-probing of the Daveron (1978) points at Moanatuatua (Section 6) surface survey was done over five 1 m^2 patches (Fig. 2) using RTK GNSS. We were able to collect 100-point measurements in about 20 minutes and thus some of the short-range spatial variation in surface height could also be captured that was more suitable for comparison to airborne LiDAR and any future satellite-based approach.

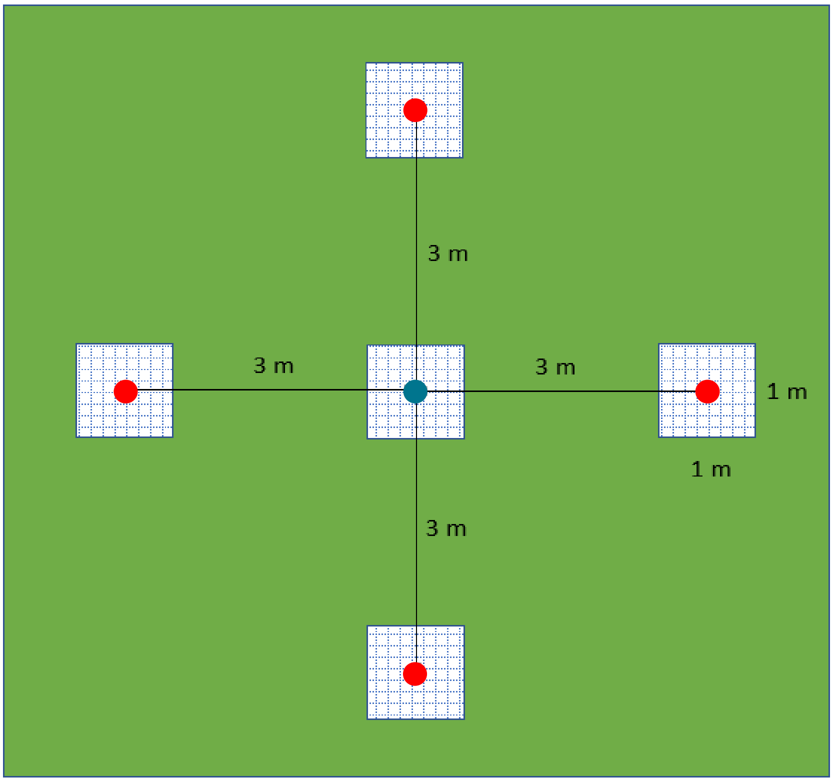

Figure 2. Layout of surface survey approach where the hatched area shows the five 1 m^2 patches that were surveyed using RTK GNSS at 25 points/m^2. These patches were centred over historic peat probing locations (Davoren (1978) points, see section 6) where the centre GPS location (blue point) was probed in addition to 4 points around the centre GPS point (red points).

4.2 Accuracy and precision of RTK GNSS

The accuracy of the Leica GS15 RTK GNSS system was tested by repeat measurements of location and height over land information New Zealand (LINZ) geodetic markers using both the LINZ and Global Survey SmartFix networks of continuously operating reference stations (CORS).

At Moanatuatua, location and height measurements were repeated on several different days spanning multiple months over a 3rd order geodetic marker (BE12, Parallel Road). Absolute accuracy varied between selected CORS. Using the Global Survey Hamilton CORS, measurements over the geodetic marker were within 0.001 ± 0.009 m (SD) of the LINZ height averaged over 30 measured heights taken at 4 different points in time (Table 1). Absolute accuracy was lower for the other CORS. The mean difference in height measured using the LINZ Hamilton CORS over the same geodetic marker was –0.022 ± 0.014 m (SD) and -0.088 ± 0.015 m (SD) using the Global Survey Cambridge CORS over the same geodetic marker. However, the standard deviation over the geodetic marker for all three CORS were similar (0.009 – 0.015 m) resulting in a 95% confidence interval that ranged between ±0.003 to 0.007 m across the three available CORS. This suggests that precision was very similar between CORS and absolute differences in height were a consistent offset as opposed to random uncertainty. Mean positional coordinate quality during the entire ground truthing campaign at Moanatuatua was 0.007 m and mean height coordinate quality was 0.013 m.

Table 1. Comparison of measured location and New Zealand Vertical Datum (NZVD) to two geodetic markers and variation associated with the available continuously operating reference stations (CORS)

Geodetic marker	CORS	Easting (m)	StdDev Easting	Northing (m)	StdDev Northing	NZVD 2016 (m)	StdDev NZVD 2016	Count	95% CI of NZVD (m)
BE12	Global Survey Cambridge	0.015	0.007	-0.007	0.012	-0.088	0.015	30	0.005
BE12	Global Survey Hamilton	0.001	0.005	-0.002	0.008	0.001	0.009	30	0.003
BE12	LINZ Hamilton	0	0.005	0.012	0.008	-0.022	0.014	16	0.007
A93Q	Global Survey Te Kawhata	0.006	0.007	-0.002	0.005	0.027	0.007	10	0.004
A93Q	LINZ Huntly	0.01	0.005	-0.007	0.009	0.02	0.004	9	0.003

Location and height were also measured at Motukaraka over a 3rd order geodetic marker (A93Q, Maramarua) for two consecutive days during calibration of the airborne LiDAR. Using the Global Survey Te Kauwhata CORS, measurements over the geodetic marker were within 0.027 ± 0.007 m (SD) of the LINZ height for the geodetic marker averaged over 10 measured heights taken over two days (Table 1). The LINZ Huntly CORS was within 0.02 ± 0.004 m (SD) of the geodetic marker height averaged over 9 measured heights taken over two days. Like Moanatuatua, the standard deviation over the geodetic marker for both CORS were relatively small (0.004 – 0.007 m) resulting in a 95% confidence interval that ranged between ±0.003 to 0.004 m. This again suggests precision was good and differences in accuracy were consistent offsets, as opposed to random uncertainty, which could therefore be adjusted for. Mean positional coordinate quality during the entire ground truthing campaign at Motukaraka was 0.007 m and mean height coordinate quality was 0.013 m.

4.3 Repeatability of RTK GNSS

The repeatability of measuring 25 points/m^2 with RTK GNSS measurements was checked by measuring a 1 square metre section of paved car park at Manaaki Whenua offices in Hamilton. Measurements were made at four points in time (between 7/05/2019 and 26/08/2019) for each of the three local CORS (Table 2). The mean height for the 1 square metre measured on each day was subtracted from the mean height calculated from the measurement at the four points in time. Based on this approach, the repeatability of measurements was good with variations between days ranging from –0.009 m to +0.007 m (Table 2) of the mean height with no important differences in repeatability between the CORS used.

Table 2. Repeatability of measurements for the three local reference stations between days

Reference station	Mean height (m)	Std Dev of height (m)	n	Variation between days (m)
Global Survey Cambridge	42.060	0.011	100	
7-May	42.060	0.010	25	0
8-May	42.061	0.010	25	0.001
9-May	42.053	0.009	25	-0.007
16-May	42.065	0.009	25	0.005
LINZ Whatawhata	42.003	0.012	100	
7-May	41.997	0.012	25	-0.006
8-May	42.008	0.009	25	0.005
9-May	41.994	0.009	25	-0.009
16-May	42.011	0.010	25	0.008
Global Survey Hamilton	41.972	0.009	100	
8-May	41.973	0.007	25	0.001
9-May	41.968	0.008	25	-0.004
16-May	41.968	0.006	25	-0.004
26-Aug	41.979	0.009	25	0.007
Mean	**42.011**	**0.038**		

4.4 Ground-based RTK GNSS survey summary

Comparison of location and height measurements were made between LINZ geodetic markers and RTK GNSS measurements. Accuracy varied between selected CORS but was within 0.001 ± 0.009 m (SD) to –0.088 ± 0.015 m (SD) of the geodetic marker height averaged over 5–10 measured heights (measurements were repeated at 4 different points in time). The standard deviation over the geodetic markers were similar (0.009 – 0.015 m) between CORS resulting in a 95% confidence interval that ranged between ±0.003 and 0.007 m of the measured height. This suggests that precision was very similar between CORS and absolute differences in height were a consistent offset which can be adjusted for as opposed to random uncertainty. Evaluation indicates vertical accuracy of RTK GNSS is in the order of ±0.01 m when 5–10 measurements are taken over a geodetic marker of known height (using the LINZ benchmark height). Precision is also likely within ±0.01 m when averaged over 25 points/m^2 .

5 Evaluation of airborne LiDAR

Airborne LiDAR was flown over Moanatuatua and Motukaraka on 18 and 19 June 2019 under optimal weather conditions (clear with little wind) except for some morning fog, which delayed flights by a couple of hours each day. Before LiDAR, survey letters were sent to landowners within the flight area and adjacent to it, to inform them of the purpose of the survey and allow them the opportunity to contact the project team with any concerns.

5.1 Data acquisition

5.1.1 Airborne data acquisition

Data were acquired using the University of Waikato's Riegl VUX-1LR LiDAR system, mounted on an EC120 helicopter, operated by Christchurch Helicopters. The LiDAR survey was based on the following parameters:

- Scanner: Riegl VUX-1LR
- Flying Height: 150 m above ground level
- Average Flight speed: 40 knots (Moanatuatua) and 45 knots (Motukaraka)
- Scan Angle: 60 degrees
- Scan Frequency: 128 Lines per second
- Pulse Repetition: 820 kHz
- Swath Overlap: 35%

Aerial photography (0.05m resolution) was acquired at the same time as the LiDAR survey. The purpose of these photos was to support the visual cross-checking of the LiDAR point cloud classification (into ground and off-ground returns).

Several parameters effect the accuracy and acquisition speed, and therefore cost, of LiDAR. For example, lower and slower flight speeds increase the point density for an equivalent LiDAR system but increase flight time and cost. Higher point density increases the proportion of ground points per m^2 and therefore the accuracy of collected data over a vegetated surface. However, a lower pulse repetition rate can also increase penetration through dense vegetation canopies but reduces the total point density for an equivalent LiDAR system at the same height and flight speed. This demonstrates the trade-off that must be considered when planning LiDAR acquisition. The effect of varying flight height, speed and point density is explored further in Section 5.4.

5.1.2 Ground support data

Correction of roving position

GNSS observations (base stations) were recorded over 3rd order LINZ geodetic marks (Global survey Waiuku Domain (GSWI) was used for the Motukaraka Survey, and Global Survey Hamilton (GSHT) was used for the Moanatuatua survey) and used to correct the roving positional track recorded by the LiDAR sensor. The base stations operate as continuous recording reference stations, as part of Global Surveys SmartFix Reference station network. Observations were acquired at both stations at a frequency of 1 Hz. The details of the reference station are as follows (NZGD2000 coordinates):

A) LINZ Benchmark Code: GSWI (Waiuku Domain)

Benchmark Position:	Latitude:	37° 15' 04.53171" S
	Longitude:	174° 43' 45.17006" E
	Ellipsoidal height (m):	50.126
Antenna:	Leica AS10	

B) LINZ Benchmark Code: GSHT (Hamilton Anglesea)

Benchmark Position:	Latitude:	37° 47' 16.40377" S
	Longitude:	175° 16' 50.39640" E
	Ellipsoidal height (m):	118.460
Antenna:	Leica AS10	

Ground based check point data

A ground survey of check point data was acquired using Leica GS15 GNSS systems operating using network RTK GNSS based on the Global Survey SmartFix network. The ground survey was conducted for a range of surface covers using plots (9 m^2) at 25 points/m^2 (225 points per plot). A circular foot, 50 mm in diameter, was fixed to the base of the survey pole to prevent it sinking into soft soil surfaces. Plots included bare soil, blueberry bushes ranging in size from about 0.3 m high to over 2 m high (Fig. 3), dense plantain based pasture (Figure 4a), maize stubble (Fig. 4b), newly sown pasture (Fig. 4c) and grazed pasture ranging from recently grazed with low pasture cover of about 1500 kg dry matter (DM) ha^{-1} (grass height ~ 0.05 m) up to heavy pasture covers of around 4000 kg DM ha^{-1} (grass height ~250 mm) (Fig. 4d). Average pasture height was measured with a ruler and pasture covers, as dry matter (DM), were assessed using a rising plate meter. The generic winter equation (DM (kg ha^{-1}) = clicks*140+500) was applied to plate meter data to estimate DM. A total of 56 plots were measured across Moanatuatua (26 plots) and Motukaraka (30 plots) totalling 12600-point measurements.

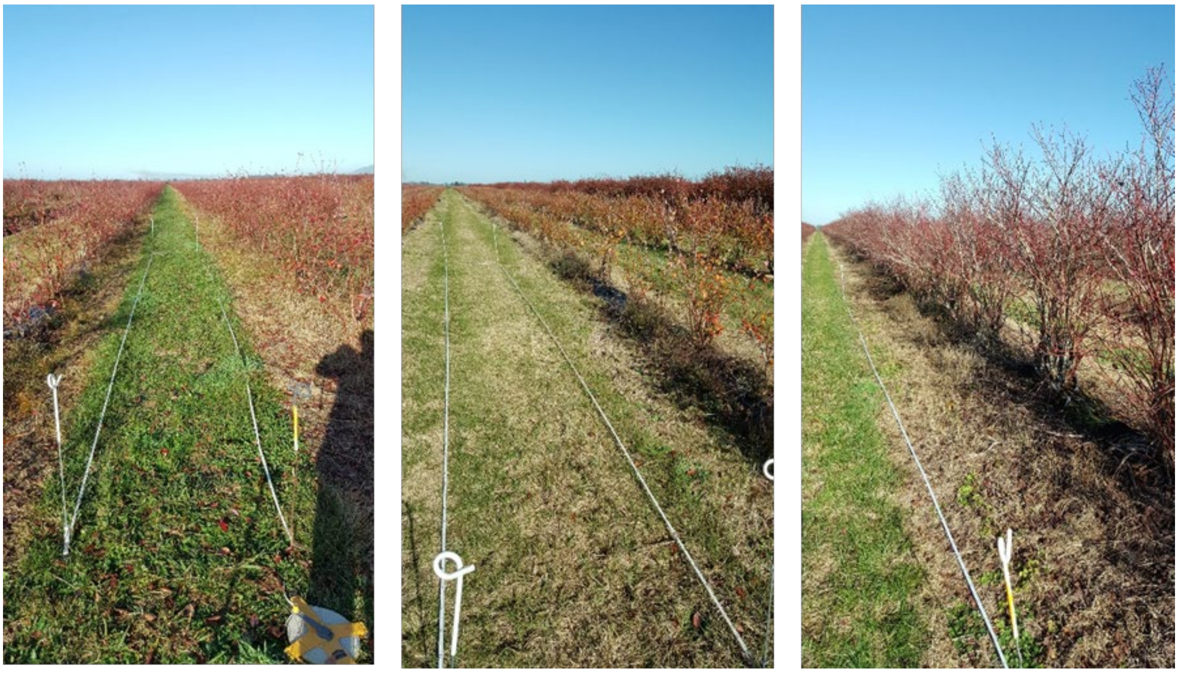

Figure 3. Ground survey plots between blueberry rows (9 m × 1 m) with blueberry bushes ranging in size from small (left), medium (middle) and large (right).

Figure 4. Ground survey plots for pastoral and cropping land (3 m × 3 m) showing an example of surface covers investigated including (a) mature plantain-based pasture, (b) maize stubble, (c) newly sown ryegrass pasture, and (d) mature ryegrass pasture.

5.2 Data processing

5.2.1 Trajectory processing

LiDAR positioning and orientation (POS) was determined using the roving GNSS inertial measurement unit (IMU) and static GNSS observations acquired using Waypoint Inertial Explorer Software. The resulting solution-maintained attitude[3] separation of less than ±2 arcmin and positional separation of less than ±0.01 m.

5.2.2 Swath calibration

Swath calibration based on overlap analysis was undertaken using the TerraScan and TerraMatch software suite. Flightline calibration was undertaken to solve for global and flightline specific deviations and fluctuations in attitude and elevation based on over 100,000 tie-lines derived from ground observations. The resulting 3D mismatch was found to be less than 0.024 m at Motukaraka and 0.004 m at Moanatuatua.

5.2.3 Ground and above ground classification

Data were classified using standard routines into ground, above ground and noise using the TerraSolid suite for LiDAR data processing (Fig. 5). The resulting point cloud density over the entire survey areas was 34 points/m^2 at Motukaraka and 49 points/m^2 at Moanatuatua. This was achieved by flying at different speeds, with typical flying speeds of 40 knots at Moanatuatua and 45 knots at Motukaraka, respectively.

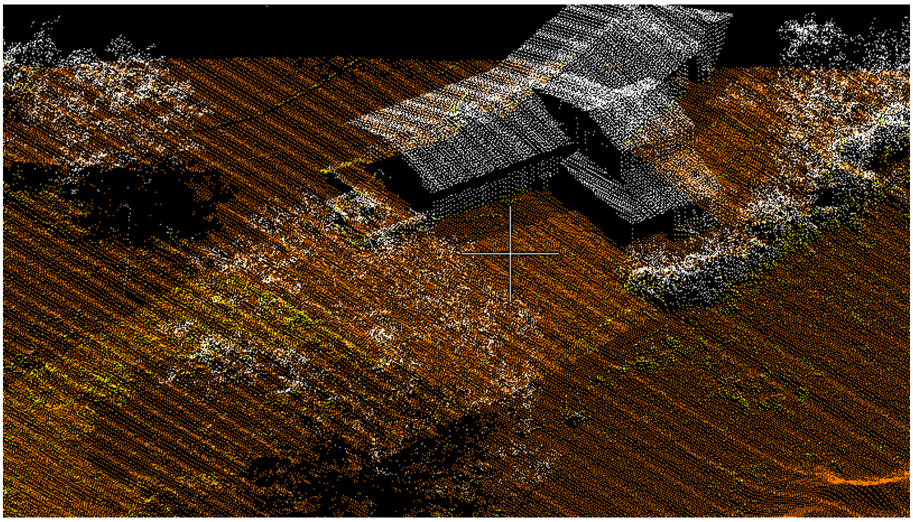

Figure 5. 3D perspective view of a section of classified point cloud from the Motukaraka survey. Data are classified as ground = orange; above ground = white; and noise (close to ground) = yellow.

[3] Attitude refers to the orientation of a body, described by the angles between the axes of that body's coordinate system and the axes of an external coordinate system. With LiDAR, attitude is normally defined as the role, pitch and heading of the instrument at the instant an active pulse is emitted from the sensor (LINZ 2016).

The breakdown of classified returns, distinguished here into ground and above-ground classes (ignoring noise), is shown in Tables 3 and 4, where the classification codes relate to ASPRS (2015) standards.

Table 3. Breakdown of classified returns at Motukaraka

Surface Type	Classification Code	Class	Number Observations
Bare Earth	2	Ground	1,098,504,491
Above Ground	3	Above Ground	114,786,353

Table 4. Breakdown of classified returns at Moanatuatua

Surface Type	Classification Code	Class	Number Observations
Bare Earth	2	Ground	638,690,669
Above Ground	3	Above Ground	45,022,964

5.3 Check point analysis and LiDAR uncertainty

The accuracy of the LiDAR data was assessed using network RTK GNSS observations acquired between 18 and 20 June 2019 (co-incident with the airborne survey, see section 5.1).

The analysis of elevation deviations between the LiDAR and ground survey observations was conducted for hard surfaces (standard data quality practice) but also for areas of pasture which are expected to have higher variance resulting from uneven ground and variable vegetation density, height and cover. Elevation deviations were dependent on surface cover.

The analysis involved two steps. The first involved the comparison of single GNSS elevation checkpoints against the nearest associated LiDAR ground returns, as specified by the American Society of Photogrammetry and Remote Sensing (ASPRS 2015). This analysis was undertaken for the Motukaraka survey, where there were a range of hard surfaces (roads) to provide unambiguous returns. In this analysis, checkpoints were therefore segmented into those from smooth, hard surfaces (roads) and those from grass-covered pasture of variable length. This comparison resulted in the following metrics describing the goodness of fit between the two datasets.

Hard surfaces (n=26):
SD[4] of elevations = 0.006 m; RMS[5] = 0.01 m; mean difference[6] = +0.009 m.

[4] SD = standard deviation of elevation differences.

[5] RMS = root mean squared difference of elevations.

[6] mean difference = average difference (positive and negative) of elevation (i.e. bias).

Pasture (n = 197; vegetation height = 0.130 m):
SD of elevation = 0.031 m; RMS = 0.041 m; mean difference = -0.026 m.

Based on these point-to-point comparisons and including the rough pasture surfaces, 68% of the LiDAR observations thus fall within 0.031 m of the observations. It should be noted that this is a conservative estimate, which implicitly incorporates uncertainty in the GNSS check-data, so that the comparison with a 'true' reference dataset is likely to reveal a higher level of performance.

To investigate the quality of the survey observations as a basis for surface elevation change measurement, a second, more detailed analysis of the LiDAR data was undertaken.

This involved the comparison of the mean elevation and variance, computed for 55 (25 from Moanatuatua and 30 from Motukaraka) sample plots (9 m^2) under a range of different land covers. For each plot between 225 and 400 (mean 245) GNSS observations were acquired using RTK double differencing, to provide estimates of the local mean, min, max and SD of elevation. The perimeter of the sample plot was then digitized and used as a polygon to extract the corresponding LiDAR data from each survey. At Moanatuatua the average LiDAR returns per plot was 483 while at Motukaraka the average LiDAR returns per plots was 246.

The resulting plot by plot comparison of the sampled mean, minimum, maximum and SD of elevations (Z) is shown for both surveys in Table 5 and 6, in which data from all landcovers has been aggregated:

Table 5. Differences between ground-based survey and airborne LiDAR elevations (Z) at Moanatuatua (n = 25 samples, average LiDAR returns per sample = 483)

	Δ Mean Z	Δ Min Z	Δ Max Z	Δ SD Z
Mean difference between samples (m)	0.001	0.015	-0.023	-0.005
SD of sample differences (i.e., SE) (m)	0.040			

Table 6. Differences between ground-based survey and airborne LiDAR elevations (Z) at Motukaraka (n = 30 samples, average LiDAR returns per sample = 246)

	Δ Mean Z	Δ Min Z	Δ Max Z	Δ SD Z
Mean difference between samples (m)	-0.003	0.028	-0.030	-0.009
SD of sample differences (i.e., SE) (m)	0.072			

In both cases, the mean difference between sampled average elevation (GNSS minus LiDAR) exhibits minimal bias (0.001 m and –0.003 m respectively), suggesting the LiDAR is well calibrated to the regional datum. The SD of the sample differences is equivalent to the Standard Error of the elevation (i.e. the SD of the sample means) and is 0.04 m and 0.072 m respectively. This metric provides a robust indicator of the variance of local average elevations at the plot scale, that would provide the basis for future change detection studies. There is some significant difference between the two surveys (0.04 and 0.07 m SE) with a high SE associated with the Motukaraka survey. Closer examination of the plot-based data revealed that this higher variance is associated with poor performance of ground estimation by the LiDAR for plots covered in plantain (Fig. 5.2a). Here, typical GNSS-LiDAR deviations varied between –0.1 and –0.016 m, suggesting limited penetration through the dense sward of broad-leaf plantain that had a typical height of 0.3 – 0.35 m. This represents an extremely challenging cover type to survey remotely and resulting errors in the measurement performance are well-within the level of expected behaviour.

Omitting the four sample plots covered by plantain reduces the SE for the Motukaraka survey to 0.059 m. This is still significantly higher than the 0.04 m found at Moanatuatua and may reflect the lower point density of this survey, which averaged 33 points/m^2 compared with 49 points/m^2 at Moanatuatua. Based on these standard errors, approximate change detection thresholds would be 0.057 m at Moanatuatua and 0.083 m at Motukaraka. Change detection thresholds were calculated based on the sum in quadrature of the SE calculated for two independent surveys (in this case assuming the same SE for each survey).

5.3.1 Effects of landcover

The 55 sample plots were subsequently analysed to examine the effects of landcover on the precision of the ground estimates provided by the LiDAR surveys. These plots encompassed a range of typical cover types that occur in the Waikato. These include:

a Grass pasture: short = 0.05 – 0.08 m; medium = 0.08 – 0.13 m; long = 0.13 - 0.2 m.

b Blueberries in three canopy height categories (small = 0.3 – < 1 m, medium = 1.0 – < 1.5 m, large = 1.5 – 2 m).

c Maize stubble.

d Plantain.

For each landcover type, the sample mean and variance of elevation was computed for the GNSS and LiDAR observations and then compared. The resulting pattern of difference between the two survey methods over the sampled plots is shown in Tables 7 and 8.

Table 7. Mean difference between ground-based GNSS survey and LiDAR at Moanatuatua (all differences in metres, GNSS minus LiDAR)

	SD of sample differences	Mean of Sample Differences (bias)
Short Grass (n=6)	0.013	0.036
Medium Grass (n=4)	0.021	0.035
Long Grass (n=5)	0.016	-0.063
Blueberries Small (n=3)	0.008	0.013
Blueberries Medium (n=3)	0.005	-0.008
Blueberries Large (n=4)	0.012	-0.015

Table 8. Mean difference between ground-based GNSS survey and LiDAR at Motukaraka (all differences in metres, GNSS minus LiDAR)

	SD of sample differences	Mean of Sample Differences (bias)
Short Grass (n=6)	0.034	0.013
Medium Grass (n=4)	0.039	0.034
Long Grass (n=5)	0.074	-0.004
Plantain (n=5)	0.048	-0.107
Maize Stubble (n=5)	0.037	0.048

These results clearly highlight the greater variance and bias associated with ground elevations surveyed by LiDAR over plantain, whereas, despite near canopy closure under the tall stands of blueberries, the low surface cover results in high quality ground returns. The performance of the LiDAR retrievals when analysed within these individual landcover classes is encouraging, particularly for the higher density survey at Moanatuatua, where typical sample differences under grass (by far the dominant landcover on peatlands in the Waikato) varies between 0.01 and 0.02 m.

5.4 Optimising pulse density, flight height and speed

The difference between the ground-truth performance of the two surveys may reflect differences in flight speed and therefore the speed of data acquisition. This resulted in significant differences between the density of ground classified returns, 33 points/m^2 versus 49 points/m^2 as discussed previously. This increased density has several potential benefits that include:

- Enhanced probability of ground detection
- Enhanced ground representation to improve swath matching
- Improved classification of ground vs off-ground returns

However, these potential gains may be offset by the additional costs associated with the flight plan required to achieve such an increase in density, i.e. by flying slower and/or lower. In order to evaluate this trade-off in more detail, the effect of the ground data density was explored numerically by thinning the higher resolution data from the Moanatuatua sampled plots. Recall, the average number of ground observations recorded in each of these 3 x 3 m plots was 483 returns. These data were then thinned by periodically sampling every second sequentially acquired point (to account for spatial representativeness), to generate a reduced resolution dataset with a mean density of 231 returns per plot. For each lower resolution plot, the mean, min and max of elevations were then estimated in the same manner as for the full dataset.

This approach generated two sets of sampled elevation metrics for each plot, which were then compared with the GNSS estimated elevations, resulting in a set of differencing (GNSS minus LiDAR) for the samples based on 100% of the LiDAR and then the decimated (50%)

dataset. These resulting comparison between the sample means, minimums and maximum elevations (Z) is shown in Table 9 (all measurements as differences in metres).

Table 9. Difference between ground-based survey elevation (Z) using GNSS compared to LiDAR where LiDAR has been artificially thinned from 100% to 50% of ground returns

	Δ Mean Z		Δ Min Z		Δ Max Z	
	100%	50%	100%	50%	100%	50%
Mean difference between samples (m)	0.001	0.001	0.015	0.010	0.007	-0.019
SD of sample differences (m)	0.040	0.040	0.034	0.035	0.012	0.060

This analysis appears to show that while the difference in the mean elevation is robust after the decimation of the data (i.e. thinning of the LiDAR) the tails of the distribution as illustrated in their most extreme form by the minimum and maximum are more prone to the effects of lower resolution sampling.

Formally, the effect of lowering the resolution of data acquisition can be tested statistically using a two-sided, paired t-test to compare for differences between the sampled GNSS-LiDAR residuals. This analysis, n=25, gives a t-score of −1.14, which has a p value of 0.26 that indicates any difference between the differences in the sample mean residuals is likely a function of chance sampling effects and not statistically significant at the 95% confidence interval.

This result suggests there may be latitude to reduce the sampling density. However, care should be exercised, as this numerical result is based on data that used the full density for swath matching and LiDAR return ground point classification, processes that would have benefited implicitly from the higher initial resolution. Despite the potential to reduce the point density and thereby reduce survey costs or increase spatial coverage, we advise a conservative approach and recommend the regional monitoring network is flown to achieve a LiDAR return ground point density of 45–50 points/m^2. Using a point density in this range should result in a change detection threshold of 0.05 – 0.06 m over typical ryegrass pasture lengths between 0.05 and 0.2 m, well within the expected surface subsidence of about 0.1 m over a 5-year period. However, detecting small differences in subsidence rates between land uses and management practices may not be possible over a 5-year monitoring period.

5.5 LiDAR data product and quantifying spatial uncertainty

Examples of the digital surface model (DSM, Fig. 6) and digital elevation model (DEM, Figure 7) produced from the LiDAR survey at Motukaraka are shown below. A DSM includes the elevations of trees, buildings and other natural and built features above bare earth; a DEM, however, represents only bare earth referenced to a vertical datum. For the future regional scale monitoring we envisage flying transects across the area of interest and producing DEMs with an estimate of spatial uncertainty that reflects not just the average positional errors but also incorporates the effects of the apparent ground roughness, which is a function (principally) of the vegetation height/structure.

A spatial representation of the land cover effect can be determined using an approach pioneered by Brasington et al. (2012) that was developed to quantify gravel particle grain size on exposed river-bed sediments from laser scan data. In this approach, a regular grid is used to sample the classified ground returns and determine the local moments (mean, SD, kurtosis and skewness) of the elevation distribution corresponding to each grid cell. The sampling grid is then detrended to disambiguate the effects of topography (low frequency elevation variability) from the observed surface roughness (higher frequency variability). The resulting detrended standard deviation has been shown to correlate well to typical surface roughness in fluvial environments.

As a test of this approach, the algorithm developed by Brasington et al. (2012) was applied to the Moanatuatua classified ground returns, and the resulting mapped pattern of detrended standard deviation of elevation shown in Figure 8. This map clearly captures the effects of pasture grazing at the paddock scale, with recently grazed surfaces characterized by a low SD of elevation (0.01 – 0.02 m), while paddocks with longer pasture have detrended SD in the range of 0.04 – 0.05 m. This metric could be combined to generate a composite measure of DEM uncertainty, combining the average positional (as an areal average) and the spatially variable roughness metric, by adding the two measures in quadrature to represent the effective summation of the two measures.

This approach to characterizing DEM uncertainty is readily incorporated into approaches to quantify elevation change by DEM differencing (see Brasington et al. 2003; Wheaton et al. 2010) and implemented using the Geomorphic Change Detection software suit (Vericat et al. 2017). This would involve the calculation of a 'total propagated error' metric for each DEM that combines a global measure of georectification accuracy with a spatial distributed measure of surface uncertainty (roughess).

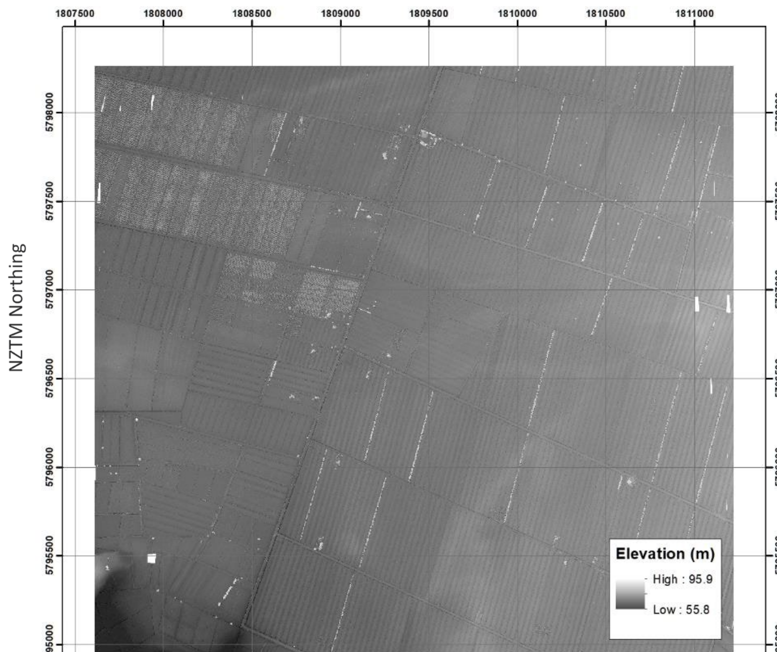

Figure 6. Digital surface model (DSM) of Moanatuatua peatland.

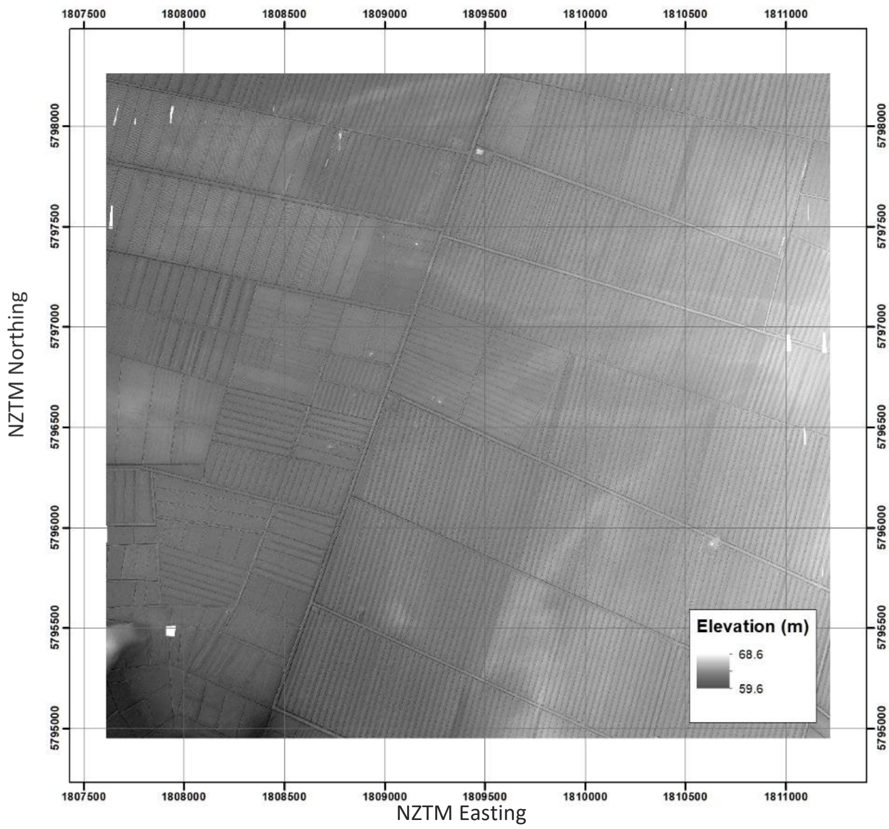

Figure 7. Digital elevation model (DEM) of Moanatuatua peatland.

Figure 8. Detrended SD of elevation of the ground returns calculated at a 0.5 m grid sampling for the Moanatuatau survey data. Recently grazed (short) pasture is characterised by low SD of elevation 0.005 – 0.01 m, while longer (rougher) surfaces have higher SD (0.04 – 0.05 m).

6 Evaluation of historic Daveron data

Historic peat depth contour maps were produced as part of a national scale peat resource survey in 1976 (Daveron 1978) and are available for most peatland areas in the Waikato Region. Point measurements of peat depth at densities of about one point per 0.5 – 0.8 km^2 for larger peatlands and one point per 0.2 – 0.4 km^2 for smaller peat areas were used to generate contour maps by Daveron (1978). The depth recorded at these point locations is not available (raw data appears to have been lost or disposed of), but the location of the points in relation to depth contours is shown on the paper contour maps. All these contour maps from the Waikato Region have recently been digitised by Waikato Regional Council. Assuming point locations and depth contours on these maps are of reasonable accuracy, re-probing of these points may enable rates of subsidence over the past 43 years to be calculated. Such data could provide early information on land use effects on peat subsidence that might take multiple 5-year monitoring intervals to extract from contemporary data. With this goal, Manaaki Whenua interpolated peat depth at the historic Daveron points (Fig. 9, red dots) and at the transect points last surveyed in 2012 (Fig. 9, blue dots, see Pronger et al. (2014)) using the Esri package in ArcGIS to create a slope map from the Daveron contour maps allowing depth interpolation at any location. Peat depth at a subset of the historic points was measured and compared with the interpolated depths.

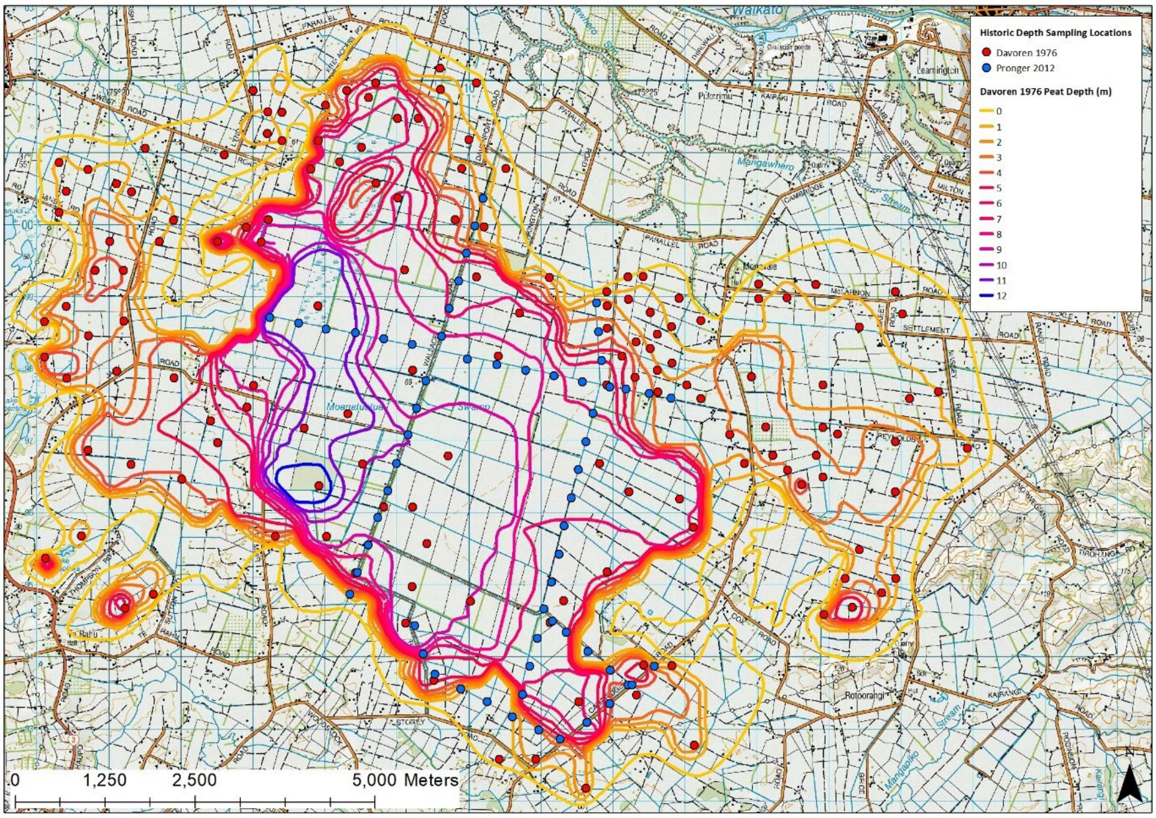

Figure 9. Peat depth contour map of Moanatuatua peatland, overlaid on a NZTM 50 map, where red circles show location of point depth measurements used to generate the contour map and blue circles show point locations of points used for the current peat subsidence monitoring indicator by Waikato Regional Council.

6.1 Re measurement of a subset of Daveron points at Moanatuatua

A subset (*n*=25) of interpolated historic Daveron points was relocated in the field using a handheld GPS (Garmin 64s) and peat depth at the point was measured using a peat probe. Probing followed the approach of Pronger (2013) where the depth at the GPS location was measured in addition to 4 points around the centre location 3 m out from the centre GPS point (see Fig. 4.1). The location of this subset of points is shown in Figure 10 (green circles). The mean of the 5-point measurements was then compared to the historic interpolated depth. Overall, there was a good relationship (r^2=0.85) between the interpolated depth in 1976 and the depth measured in 2019 (Fig. 11, panel a). We also examined the relationship between the residuals (vertical distance of point from fitted line) and the distance the historic Daveron points were from the contour lines used to interpolate the point depth (Fig. 11, panel b). The residuals did not appear to increase in size as distance from contour lines increased, indicating selecting points close to contour lines is of little additional value.

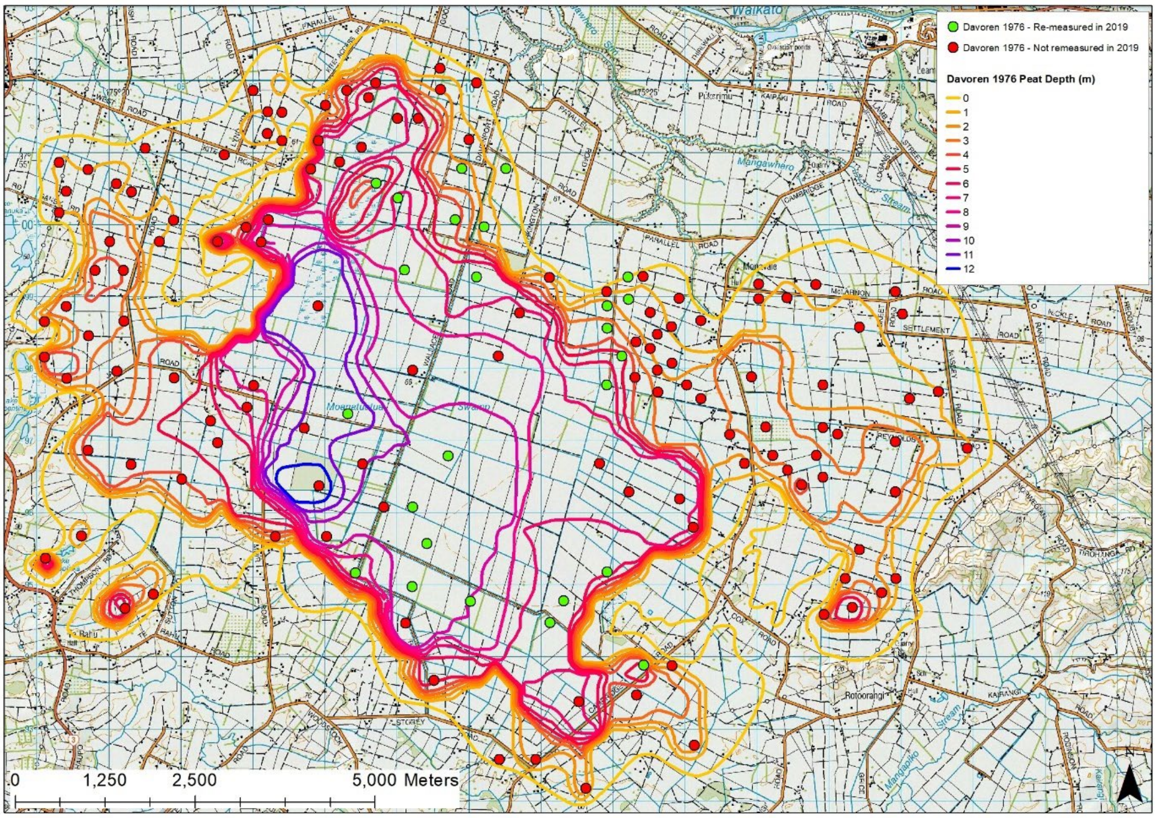

Figure 10. The subset of 1976 Daveron points where peat depth was remeasured in 2019 (green circles) compared with all Daveron points at Moantuatua (red circles).

Of the 25 historic points, 23 were on dairy or dairy support farms, with two points on blueberry orchards. For the 23 points on dairy farms, the mean interpolated peat depth was 5.52 m in 1976 and the mean measured depth in 2019 was 4.04 m resulting in a mean depth reduction of 1.48 m with a 95% confidence interval of ±0.6 m. This calculates to a mean subsidence rate of 0.034 m yr^{-1}, with a 95% CI of ±0.014 m. The mean subsidence rate is higher than the most recent subsidence estimate for Moanatuatua of 0.021 m yr^{-1} between 2002 and 2012 but similar to the historic subsidence rate of 0.033 m yr^{-1} between the 1920s and 2012 (Pronger et al. 2014). Drainage and agricultural development at Moanatuatua did not start in earnest until the 1950s (Wallace 1978) and drainage of some areas to the south did not occur until the 1980s (Story, pers. com. 2012). It is likely higher subsidence rates estimated from the Daveron points occurred because the early period (from 1976) included some rapid initial settlement not captured in the period between 2002 and 2012.

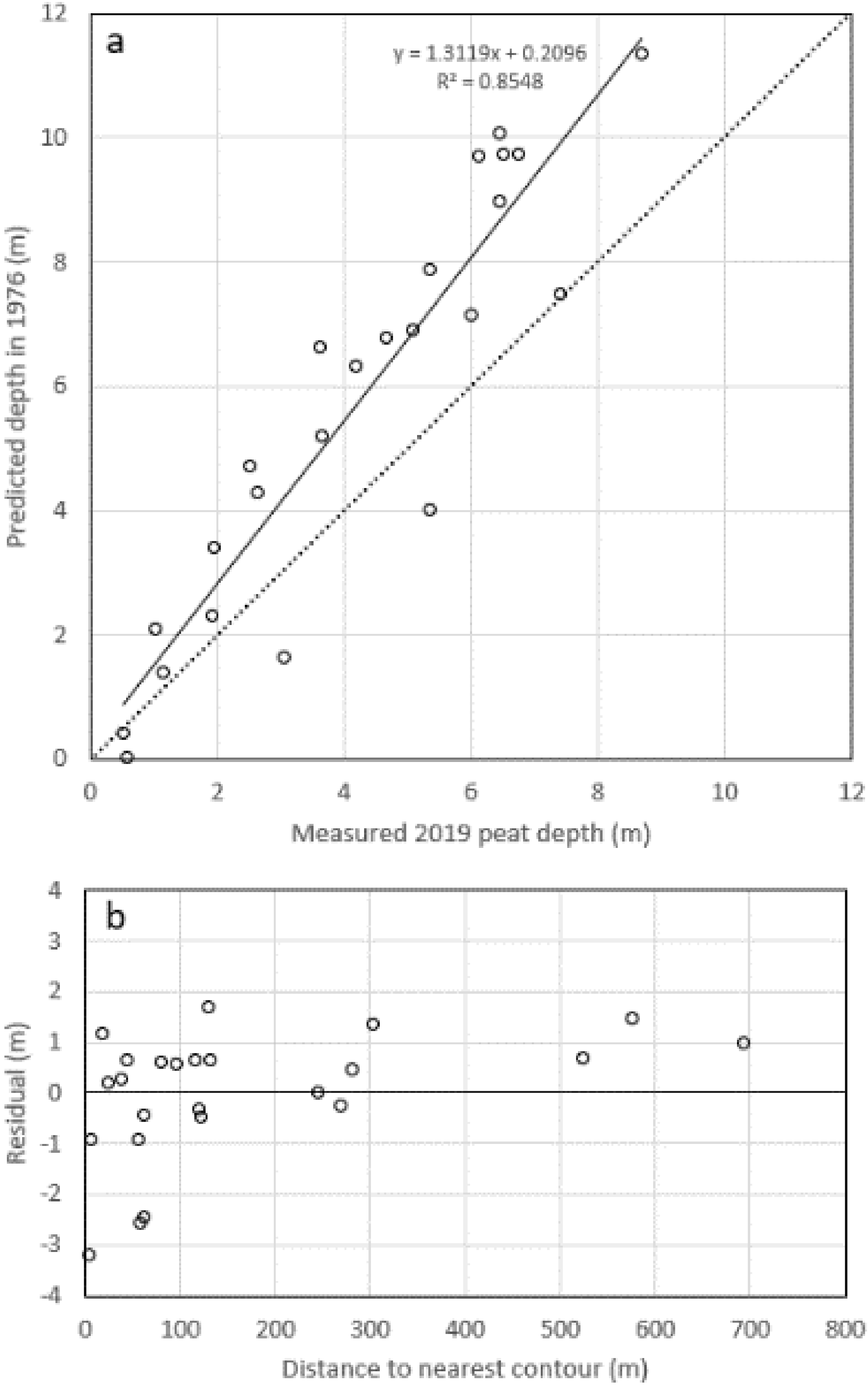

Figure 11. Relationship between predicted depth at historic point locations in 1976 and peat depth measured at the same point in 2019 (panel a) and residual from fitted line in panel a and distance from nearest contour used to predict 1976 peat depth (panel b).

6.2 Evaluating the size of the difference in subsidence between land uses that could be detected from historic Daveron data

To estimate the difference in peat depth that would need to have occurred to detect a significant difference between land uses, we followed the approach taken by Pronger (2013). The standard deviation within each land use was assumed to be the same (1.48 m, n=23), and we assumed all criteria for a standardised students t-test could be met. For this scenario a difference in depth change between land uses of ±0.88 m was required for a statistically significant difference from 23 sites over a 43-year period. Therefore, the simulation suggests that a land use would need to have a total depth change of less than 0.60 m (1.48 m minus 0.88 m) or more than 2.36 m (1.48 m plus 0.88 m) over the 43 year period to be statistically differentiated from the dominant land use (dairy grazing). This equates to a subsidence rate of 0.014 m yr^{-1} for a land use with a lower subsidence rate or 0.055 m yr^{-1} for land use with a higher subsidence rate or about a 20-mm difference in annual subsidence rates between land uses.

Differences in subsidence rate of 0.02 m between land uses may be plausible in more extreme situations, for example under continuous cropping or where the water table is maintained very close to the surface. Using this historic Daveron data, it is likely significant differences in subsidence rates will not be detected between some land uses where differences are expected to be small (e.g. dairy compared with drystock). In a situation where no difference between land uses was detected, we would only be able to say that if a difference does exist it is less than 0.02 m yr^{-1}.

6.3 Evaluating the importance of going back to point locations as opposed to random locations on the Daveron surface

It would be advantageous if the design of the regional network was not limited by the Daveron point locations (red circles in Fig. 9). The Daveron depth contour maps allow for the 1976 peat depth to be predicted at any point across the peatland. To evaluate the importance of returning to the point used to generate the Daveron surface compared with a random location on the surface, we compared the strength of the correlation between the predicted depth in 1976 and depth measured at the point in 2019 (Fig. 10a) to the correlation between the predicted depth in 1976 at the points measured in the 2012 (Fig. 12a) and 1925 surveys (Fig. 12b) (points from the 2012 and 1925 surveys are the same locations and shown as the blue circles on Fig. 9). These points from the 2012 and 1925 surveys have no direct link to the Daveron surface so should represent the effect of going to any location on the surface. Correlation strengths were similar between these two approaches. Consequently, there is limited value in constraining network design by returning to the historic points as opposed to anywhere on the surface.

We also examined the relationship between distance from the contour line and the residuals from the relationship between the predicted depth in 1976 and the depths measured in 2012 (Fig. 12c) and in 1925 (Fig. 12d). Residuals were evenly distributed with no apparent increase with increasing distance from contour lines. This indicates that revisiting a random location on the Daveron surface is an appropriate approach.

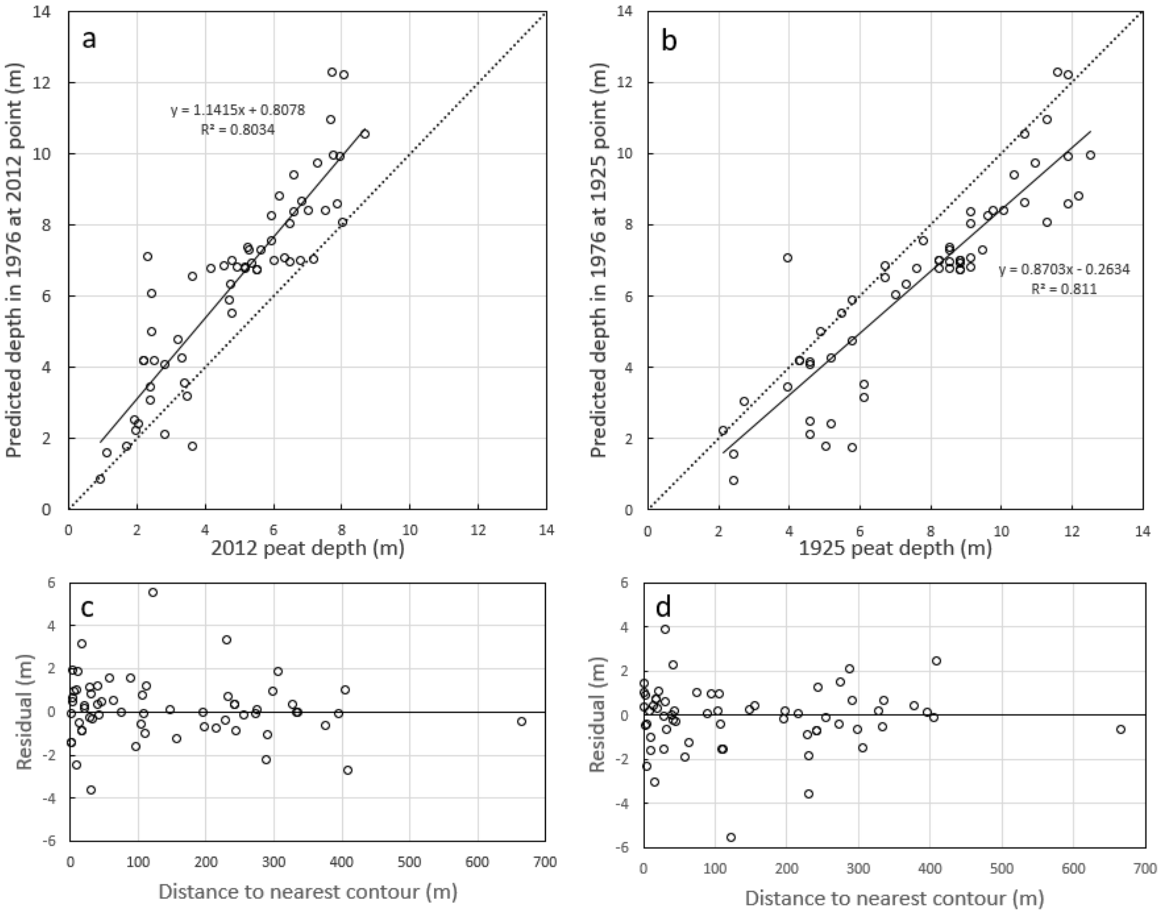

Figure 12. Relationship between the predicted depth in 1976 and depths measured at the location in 2012 (panel a) and 1925 (panel b) and the relationship between the residual and distance from the nearest contour line for 2012 (panel c) and 1925 (panel d).

7 Peat surface oscillation

The surface of natural peatlands can oscillate seasonally because of changes in water-table (Fritz et al. 2008). Fritz et al. (2008) measured changes in surface elevation along a transect across Opuatia peatland. Over an annual period, surface elevation changes at points across the transect ranged from 0.032 to 0.28 m (mean of 0.149 m) and this change was coupled with changes in the water table depth. The magnitude of this process in drained and consolidated agricultural peatlands is often assumed to be minimal, but data to support this assumption are lacking. Depending on its magnitude, peat surface oscillation (PSO) has potential to confound shorter term (e.g. 5-yearly) re-survey intervals where a total reduction in surface height of about 0.1 m is expected (0.02 m y^{-1}).

7.1 Repeat surface survey

The timeframe of the development phase of this project limited our ability to determine the magnitude and spatial variability in peat surface oscillation (PSO). However, as part of an aligned MSc project (Glover-Clarke, 2020), peat surface height was monitored on two dairy farms (Farm M and Farm G) at Moanatuatua using repeat surface survey (RTK GNSS) across transects (~180 m) started in late January 2019 and continued at a frequency of about once per month (Fig. 13). At farm M the surface measurements suggest a reduction in surface height of close to 0.04 m occurred between January 2019 and May 2019 during the dry late summer and autumn periods. The surface height then recovered between May and August to close to January height. At farm G the surface measurements suggest a reduction in surface height of close to 0.06 m between January 2019 and May 2019 followed by a recovery of about 0.035 m between June and August.

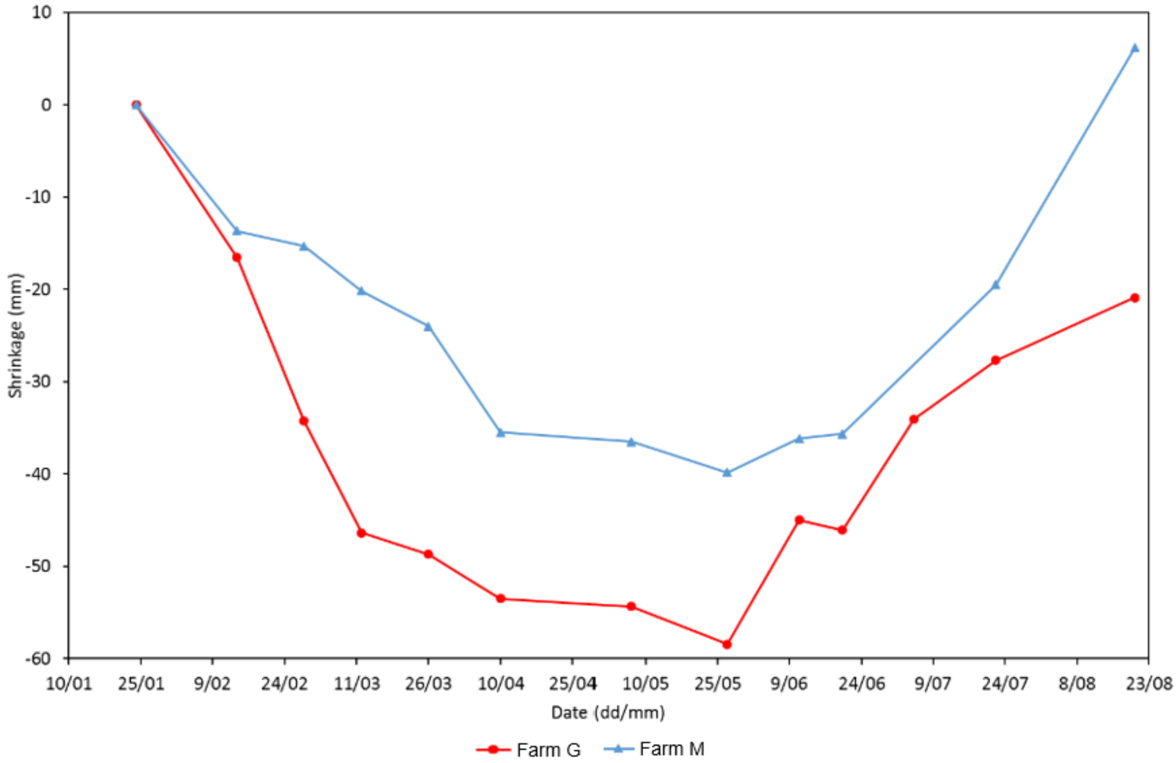

Figure 13. Repeat RTK GNSS survey of surface height through time at Farm G and Farm M.

7.2 Paired pressure transducers

In March 2019, paired pressure transducers were installed to monitor water table depth and peat surface oscillation continuously at three-point locations across Farm G and Farm M following the approach of Fritz et al. (2008). Preliminary data (Fig. 14) indicates a reduction in surface height between March and late-May of between about 0.05 and 0.08 m across the two sites at Farm G followed by a recovery of about 0.04 m by August. At Farm M there was a reduction of 0.03 m between March and late-May and a recovery of about 0.025 m by August. These data suggest a clear linkage between large rainfall events, increased water table depth and peat surface elevation increases that was especially evident following a large rainfall event in late July. These data require some checking and calibration but support the surface survey measurements. Calibrated data will be presented in the final monitoring network report.

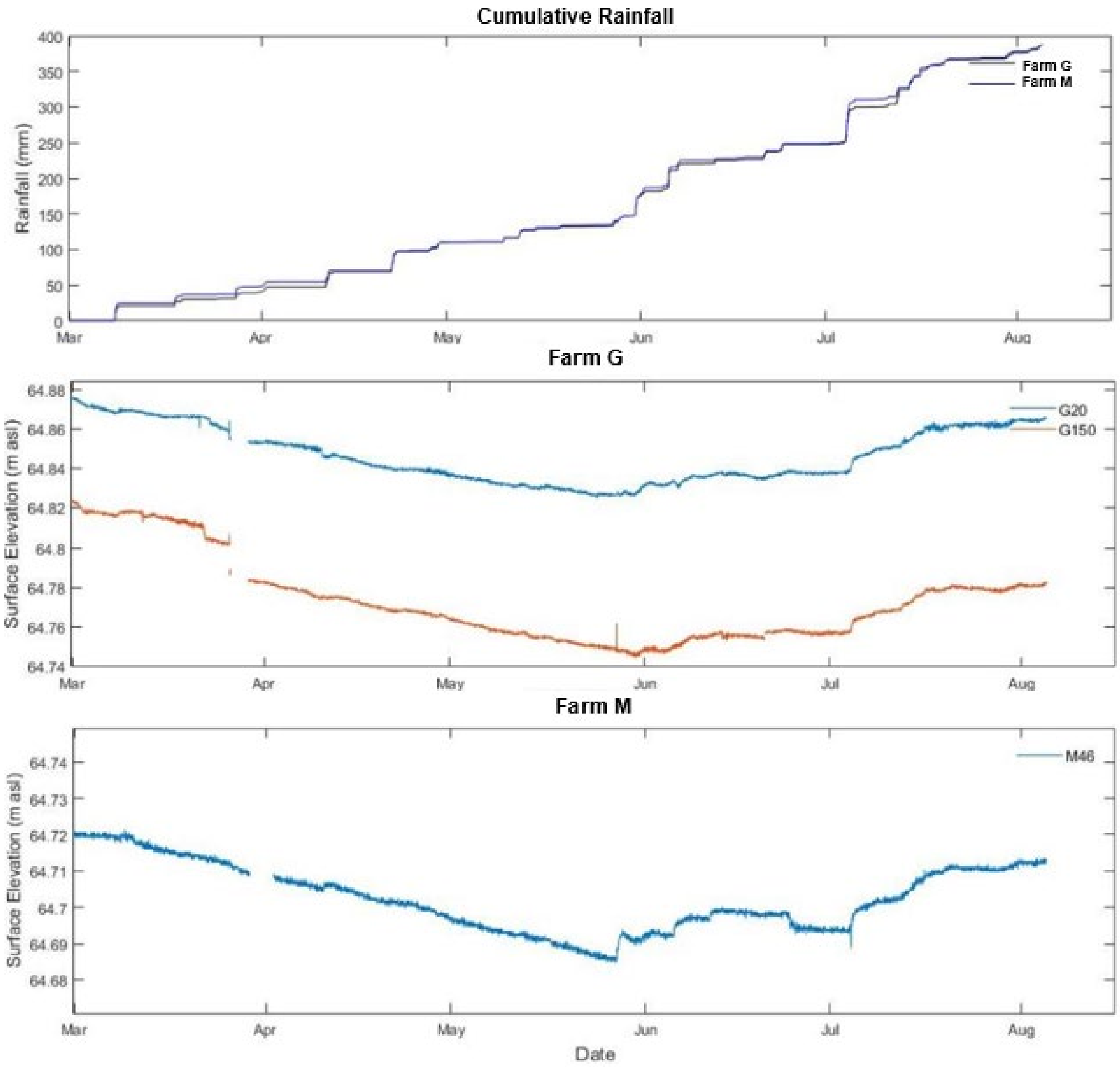

Figure 14. Cumulative rainfall and preliminary data from paired pressure transducers at Farm G and Farm M to continuously monitor peat surface oscillation following the approach of Fritz et al. (2008). Note the surface elevation graphs show data from two monitoring sites at Farm G (G20 and G150) and one site at Farm M (M46).

7.3 Static GNSS measurements

A Trimble R8 GNSS was also set up at the Farm G site to test this approach to measure changes in surface height continuously. Positional data were recorded by the R8 and stored on an internal SD card that was downloaded at regular intervals (about every 3 weeks). The collected data required post-processing to calculate accurate changes in surface height. During post processing the positional data collected was found to be inconsistent and a fault with the R8 was suspected. Funding to repair or replace the R8 was not available so this method was discontinued and deemed not necessary because the paired pressure transducer approach described above (Section 7.2) was cheaper and worked well to continuously monitor surface height.

7.4 Peat surface oscillation summary

Preliminary investigation into the magnitude of PSO on drained agricultural peatlands indicates intra-annual PSO could be of a similar order of magnitude to the expected surface level change over a 5-year monitoring interval. This could be problematic for 5-yearly monitoring, and further research is needed to quantify the spatial and temporal variation in the magnitude of PSO. Fritz et al. (2008) showed that PSO was strongly coupled with water table variation and consequently it may be possible to carry out 5 yearly monitoring at the end of winter when water tables are likely at their highest and relatively consistent between monitoring intervals.

8 Limitations to regional monitoring network design

The next section of the report overviews landcover on peatlands in the Waikato region and a summary of spatial layers, and their limitations, that could be used to inform monitoring network design. These are included in this report to inform initial discussion on monitoring network design.

8.1 Land uses of interest are not well represented spatially

Peat soils cover 100,600 ha[7] of the Waikato region and the distribution of land covers within this area are shown in Figure 15 based on the Land Cover Data Base (v4.1). About 80,610 ha (80%) of this area is used for primary production including agriculture, horticulture and forestry. The remaining area is broadly classified as environmental services (19,076 ha, 19% of area), urban (895 ha, 0.9%) and infrastructure (56 ha, 0.1% of area). For this project we are focusing on drained peat used for primary production. High producing exotic grassland, used predominantly for dairy or dairy support, covers about 78,638 ha (98% of area) of the primary production area. Short rotation cropland covers about 819 ha (1% of area), orchards about 304 ha (0.4% of area), forestry about 737 ha (1% of area) and low producing grassland about 112 ha (0.1% of area). Therefore, designing a network that is spatially representative with a distribution of sample points spread across all land uses of interest (high producing grassland, cropping and orchards (blueberries) is difficult.

[7] This area estimate is based on the extent of Organic Soils within the Waikato Regional Council boundaries estimated from the combination of S-map where complete and the Fundamental Soils Layer where S-map data were not available and was correct at the time of writing. However, since this report was written area estimates for Organic Soils have changed based more recent soil mapping.

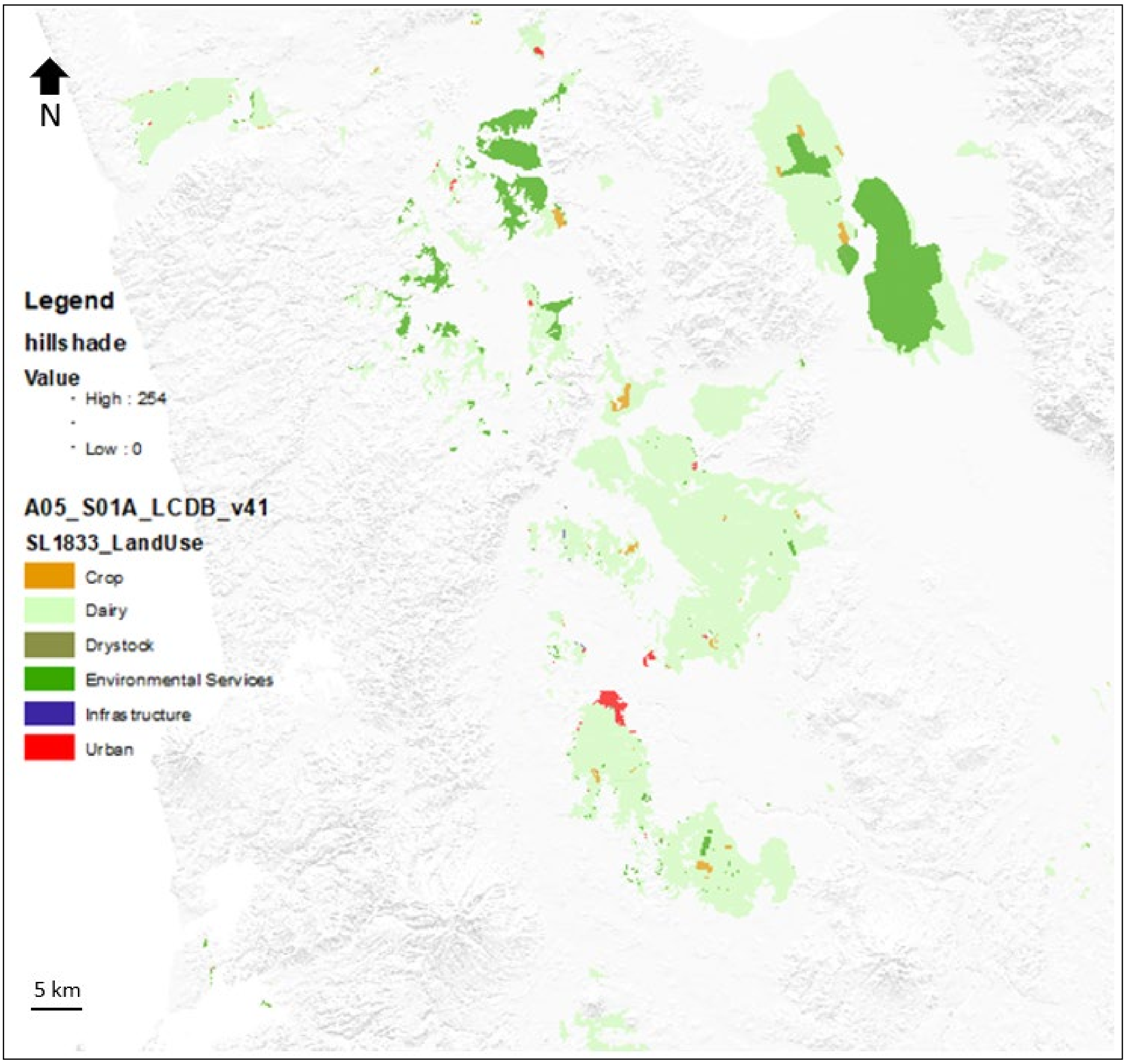

Figure 15. Distribution of land covers on peat soils in the Waikato Region from the Land Cover Data Base (V4.1).

8.2 Spatial layers include incomplete information

Spatial layers required to inform sampling network design include peat soil extent, peat depth, land use, and drainage management. Each of these layers have several limitations that were discussed in detail in the previous report (see Pronger et al. 2019), these are summarised in Table 10 below.

Table 10. Summary of spatial layers and their limitations

Spatial layer	Limitation	Approach to overcome limitation
Peat soil extent and type	Data spread across sources (S-map, FSL, and lower Waikato survey). Delineation of boundary between Gley and Organic soils difficult. Fibric, Mesic, Humic group changes through time.	Integrate data sources taking most up to date data source for each area. Where Gley soils are found at sample location relocate point to peat. Where wrong soil Group located, record new Group.
Peat depth and historic monitoring location	Peat depth information based on out of date contour depths from Daveron (1978) where supporting data (depth and coordinate location) has been lost.	Need to capture the range of peat depths and despite continued subsidence, the Daveron (1978) contours will still help ensure the range of depths are represented.
	Non Davoren (1978) peat depth information spatial coverage is limited or poorly located.	Use a mix of all available historical peat depth monitoring locations, e.g. using Davoren (1978) and Non Davoren (1978).
Land use	LCDB does not differentiate land use only land cover. Agribase information is often outdated or information is missing and Agribase is not suitable for identification of long-term cropping.	Bolster information with local knowledge, examination of historical imagery to help identify areas of interest (i.e. continuous cropping).
Drainage management	No information on drainage type or depth of drainage (only drainage management). Disturbance effect associated with conversion of hump and hollow to paddock boundary drains must be considered.	Use local knowledge of drainage type and during monitoring collect and record information on drainage type and depth.

9 Summary and recommendations

Testing of the proposed GNSS surface survey approach and helicopter-based LiDAR has been completed and uncertainties quantified. Additionally, the potential for historic data to provide early information on differences in subsidence rate between land uses has been evaluated. The magnitude of intra-annual PSO has also been investigated, but more work is required.

9.1 Surface survey

Surface survey using RTK GNSS is suitable for detecting surface height change of about 0.1 m expected over 5-yearly monitoring intervals. Accuracy for RTK GNSS is generally expected to be ±0.02-0.04 m. However, our evaluation suggests accuracy is in the order of ±0.01 m when 5–10 measurements are taken over a geodetic marker and precision is also likely within ±0.01 m when averaged over 25 points/m^2 .

9.2 Airborne LiDAR

Airborne LiDAR is suitable for detecting a change in peat surface height in the order of 0.1 m over a 5-year monitoring interval. LiDAR flown at a ground return density of about 45–50 points/m^2 will be expected to have a change detection threshold of 0.05 – 0.06 m but uncertainty increases with pasture height and for areas with very high pasture covers a significant difference may not be detected at a 5-yearly monitoring interval. We recommend spatial uncertainty is estimated based on the surface roughness approach outlined in section 5.4 and LiDAR is flown in late winter when pasture covers are generally low to minimise the potential for high pasture covers preventing detection of change.

9.3 Peat surface oscillation

Evidence collected over the past months indicates seasonal PSO is of a similar order of magnitude to expected change over a 5-year monitoring period. Further research is required to better understand the magnitude, drivers and spatial variation in PSO. Currently PSO is a risk to detection that is difficult to quantify. We suggest monitoring is done in late winter or early spring to ensure water table levels are relatively consistent between monitoring intervals and research is continued (see section 9.5).

9.4 Historic data

Re-probing of the historic Daveron data may detect a difference in subsidence rates between land uses if a mean difference of 0.02 m per year occurred over the 43-year time period. Evaluation of the importance of going back to the Daveron points compared with anywhere on the surface indicated there is little gained by going back to the historic points. We recommend using the surface as opposed to the points to avoid constraining monitoring network design based on historic data.

9.5 Network design

The next step is to design the regional peat subsidence monitoring network. Several factors need to be considered including the limitations of spatial layers available to inform network design and the distribution of land uses. WRC have requested a network that provides good spatial coverage of the region while capturing the effects of peat type, peat depth, land use, drainage management, and time since drainage. A hierarchy of importance of these factors needs to be settled upon while considering the limitations of information on each factor of interest (see section 8 and Table 10). A workshop will be held with WRC representatives to settle on an agreed approach based on the quality of existing information and the importance of each factor.

Additionally, during scoping of this project, it was suggested to sample 100 ground-based point measurements across the Waikato region coincident with the regional airborne LiDAR survey. At each of these points it was proposed to measure peat depth and ground surface height using RTK GNSS. However, given the SD of sample differences between LiDAR acquired at ~50 points/m^2 (Moanatuatua) and ground-based checkpoint data for grass (the dominant landcover) were between 0.01 and 0.02 m (Table 7), there is limited value in one-off ground-based RTK GNSS spread across the region (beyond expected ground truthing of LiDAR survey). Additionally, strong correlation between historic Daveron (1978) peat depths and contemporary measurements at Moanatuatua (Section 6) indicates the Daveron data could be adjusted to interpolate approximate current peat depths for the region.

Furthermore, the higher point resolution of the Daveron data will likely provide more accurate prediction of spatial variation in depth compared with 100 points spread across the region. We suggest the budget that was originally allocated to the 100 ground-based point measurements would provide greater long-term value if used toward establishing several long-term continuous monitoring sites spread over a range of land uses and potentially spread across the region. Continuous monitoring sites will improve our understanding of the magnitude and spatial variation in peat surface oscillation, which is likely critically important for the success of the regional monitoring network, and will also provide detailed information on spatial variation in subsidence and on the response of subsidence to climate, land use and management. Further discussion with WRC is required to determine if this approach is favourable.

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