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A survey of Waikato peat resources

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Prepared by	Alice Wheatley-Wilson & Justin Wyatt
For	Waikato Regional Council Private Bag 3038 Waikato Mail Centre HAMILTON 3240
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List of Abbreviations

Abbreviation	Term
AEM	Airborne Electromagnetic
AGOL	ArcGIS Online
AIC	Akaike Information Criterion
CORS	Continuously Operating Reference Station
DEM	Digital Elevation Model
DOC	Department of Conservation
EBK	Empirical Bayesian Kriging
EMI	Electromagnetic Induction
ERI	Electrical Resistivity Imaging
FSL	Fundamental Soils Layer
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPR	Ground Penetrating Radar
IDW	Inverse Distance Weighting
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
MWLR	Manaaki Whenua – Landcare Research
NZSC	New Zealand Soil Classification
NZTM	New Zealand Transverse Mercator
NZVD	New Zealand Vertical Datum
OC	Organic Carbon
OCP	Observed Control Point
OS	Organic Soil
RMSE	Root Mean Square Error
RTK	Real Time Kinematic
S-Map	Soil Map
SOC	Soil Organic Carbon
TC	Total Carbon
TOPO	Topographic Point
VRS	Virtual Reference Station
WRC	Waikato Regional Council

Abstract

Peat thickness measurements at the regional scale underpin quantification of peatland resources, understanding peatland condition, and assessing change through time. This report presents an updated regional assessment of peat thickness for the Waikato, integrating new 2023 field measurements with the 1978 Davoren regional peat survey, historical well records, and targeted site investigations, with historic thicknesses adjusted to a 2023 datum using subsidence rates from Pronger et al. (2014). Peat thickness was measured at approximately 800 sites using Dutch auger and steel probe methods, with five probing points per site and concurrent RTK GNSS surface elevation. Spatial interpolation used regression kriging in R, with a spline trend and variogram fitted separately for each peatland. Modelled surfaces agreed well with measured thickness (R^2 = 0.85), and field-measured surface elevations matched the 2021 LiDAR digital elevation model closely (R^2 >0.99). Modelled peat volumes were estimated for all major Waikato peatlands, including approximately 0.7 km^3 for the Hauraki peatlands, 0.26 km^3 for Komakorau, and 0.21 km^3 each for Moanatuatua and Rukuhia. Maximum measured peat thicknesses of 11–12 m were recorded at Kopuatai, Moanatuatua, Rukuhia, and Te Mimiha. This study represents the first regional-scale inventory of modelled peat thickness across Waikato peatlands, and to our knowledge, no comparable regional-scale kriged peat thickness inventory currently exists for any other region of New Zealand. The methods are transparent, reproducible, and transferable, providing an updated regional assessment of the Waikato peat resource. The dataset also establishes a baseline for future monitoring of peat thickness and surface elevation change and provides a framework for peatland inventories in other regions of New Zealand.

Executive summary

Aim and objectives

This report presents an updated regional-scale inventory of peat thickness measurements and modelled peat thickness contours across major peat bogs in the Waikato region. The primary objective was to collect, collate, process, and spatially model peat thickness data from multiple survey campaigns using reliable and reproducible methods. Additionally, the results enable robust comparisons between bogs and provide a baseline to support future monitoring of peat thickness change, peat surface elevation change, and peat resource assessments.

The objectives of the study were to:

- compile and collect peat thickness and surface elevation data across major Waikato peatlands;
- develop peatland-scale maps and estimates of peat thickness and peat volume;
- evaluate the performance of the field and modelling methods; and
- establish a dataset to support future peatland assessment and monitoring.

Methods in brief

Peat thickness measurements were obtained using Dutch auger and steel probe methods consistent with previous Waikato peatland investigations, including the 1978 Davoren survey from which many survey locations were derived. Approximately 800 sites were assessed across the region, with five probe measurements collected at each site where possible. Surface elevation was recorded concurrently using RTK GNSS equipment.

Peat thickness was modelled using regression kriging in R. Interpolation was constrained within an Organic Soil modelling boundary developed from S-Map, the Fundamental Soils Layer, historic peat boundaries, and systematic boundary refinements. The boundary was used only for modelling purposes and should not be interpreted as a definitive peatland extent.

For this study, *peat thickness* was defined as the vertical distance between the ground surface and a clearly identifiable peat–mineral interface. Measurements were treated as true peat thickness only where peat directly overlaid firm mineral substrate and the interface could be confidently detected. In some areas, particularly Huntly and parts of the Lower Waikato peatlands, available information represents depth to firm mineral substratum rather than true peat thickness. These measurements were retained because they provide useful information on peatland stratigraphy but should be interpreted accordingly.

Key results

Results are presented as peat thickness contour maps and cross-sectional profile transects for each peatland to illustrate the spatial distribution and basin geomorphology of the remaining peat resource. Table A summarises the key outputs for each peatland, including modelled area and peat volume, average and maximum measured peat thickness, and the number of survey sites contributing to the analysis.

Table A. Summary of Waikato peat thickness data, including estimated area, approximate peat volume based on modelled thickness, average (mean) and maximum thickness calculated from site measurements, and the total number of sites sampled in each area.

Area	Area (km^2)*	Volume (km^3)	Average thickness (m)	Maximum thickness (m)	Total number of sites
Hauraki** (includes Hauraki, Hauraki East, and Kopuatai)	243.6	0.7	3.47	12	453
Hoe o Tainui	23	0.05	5.41	9.44	19
Huntly**	29.2	0.01	2.90	8.79	266
Kainui	29.5	0.015	2.21	5.84	31
Komakorau	225.7	0.26	2.18	10.54	289
Lower Waikato** (includes Whangamarino)	68.1	0.01	2.22	7.49	52
Moanatuatua	86.8	0.21	3.65	11.00	209
Ohinewai	14.6	0.005	6.30	9.50	13
Ohote	11.2	0.003	2.30	3.66	19
Orini	16.6	0.05	4.98	8.19	28
Rukuhia	66.6	0.21	6.05	11.10	202
Te Mimiha	12.6	0.01	8.01	11.76	7

*Area is reported as the boundary displayed in Figures 11–39 in the results – only upper values are shown. Area and volume are based on modelled contours, while maximum depth and thickness are measured values not interpolated results. Peat volume was calculated by integrating modelled peat thickness across thickness classes (section 2.5.5) and is not equal to area multiplied by average measured thickness.

**These areas represent more than one related (geographically or hydrologically separated) peatland.

Model performance was assessed by comparing modelled peat thickness with field measurements and by comparing field-measured surface elevation with the 2021 LiDAR-derived digital elevation model (DEM). Peat thickness predictions showed strong agreement with measured values ($R^2 \approx 0.85$), while measured and LiDAR-derived surface elevations were extremely closely correlated ($R^2 > 0.99$). These results indicate that the modelling approach reliably represents peat thickness patterns at the peatland scale and that the LiDAR DEM is suitable for representing peatland surface topography.

Discussion

The results provide the most comprehensive regional assessment of Waikato peat thickness currently available and use a transparent, reproducible regional-scale regression kriging approach. The contour maps and volume estimates improve understanding of the spatial distribution of the peat resource and provide a basis for comparison with historic and future surveys. In an international context, Waikato peatlands are generally thicker than many peatlands reported elsewhere in the world. While peatlands globally are often reported to have average thicknesses of 1–3 m and maximum depths of 5–10 m, one-third of the Waikato peatlands assessed in this study had mean peat thicknesses greater than 3 m, and several recorded maximum measured thicknesses exceeding 10 m.

Despite the overall confidence in the methods and model, several limitations should be considered when interpreting the results. Peat thickness estimates are influenced by uncertainty in peatland boundary delineation and by the density and spatial distribution of measurements.

Model performance generally improved with increased site density; however, local variability and very thick peat deposits may be underestimated because regression kriging produces a smoothed surface. Additionally, Huntly and parts of the Lower Waikato measurements represent depth to firm mineral substratum rather than true peat thickness. So, while useful for regional comparison, these data are not directly equivalent to peatlands with thickness measurements only. Overall, the field and modelling methods were robust and fit for purpose, producing reliable peatland-scale maps while remaining transparent and reproducible for future surveys.

Conclusions and next steps

This project provides an updated regional inventory of peat thickness across the major Waikato peatlands, improving understanding of the distribution, extent, and volume of the region's remaining peat resource. The resulting maps and datasets represent a comprehensive regional assessment and provide a transparent, reproducible foundation for future peatland research and management. The methods are readily transferable to other regions of New Zealand, and the dataset provides a basis for future monitoring of peat thickness and surface elevation change. Future work should focus on improving peatland boundary definition and increasing sampling density to increase modelling accuracy and to better quantify change through time.

1 Introduction

1.1 Background

The Waikato Region contains approximately 84,000 hectares of Organic Soils, which developed over the past 10,000 to 14,000 years (McGlone 2009; Wheatley-Wilson and Wyatt 2024)[1]. Organic Soils (also often called 'peat soils') are slowly formed over thousands of years, from the accumulation of partially decomposed plant-derived organic matter (at a rate of about 1 mm per year) in areas where high water tables cause anaerobic conditions and slow decomposition processes (Goodrich et al. 2017). In some areas, this organic material reaches thicknesses of over 10 metres (Selby and Lowe 1992).

Since the early 1900's, extensive drainage of Organic Soils has taken place across the region and wider New Zealand, primarily to enable pastoral agriculture, with smaller areas converted for cropping, horticulture, and urban development (Pawson and Brooking 2013). Organic Soils are under threat of being greatly reduced or disappearing completely due to peat subsidence. Ongoing artificial drainage for economically productive uses lowers the water table and causes peat subsidence. Processes contributing to subsidence include structural collapse of the peat (through shrinkage above the water table and consolidation below the water table) and increased oxygen diffusion into the soil (increasing decomposition rates and leading to the permanent loss of soil organic carbon (SOC) through oxidation as carbon emissions)[2]. Subsidence processes lead to a reduction in peat volume and surface elevation. Farming practices further intensify these processes by adding nutrients and altering pH, both of which enhance microbial activity and decomposition rates. Organic Soils are also at risk of loss and degradation due to fires, which can affect both natural and drained systems (Wilkinson et al. 2020; Department of Conservation 2025). In some cases, shallow Organic Soils present in wetlands before colonisation have been lost due to drainage, and are now represented by different soil orders, such as Gley Soils[3].

Of the 84,000 hectares of Organic Soils mapped in the Waikato today, 65,000 hectares of these are drained (Wheatley-Wilson and Wyatt 2024). The remaining ~20,000 ha are intact peatlands in their near-natural form. Notable intact peatlands found within the Waikato include Kopuatai Peat Dome (Hauraki), Moanatuatua Reserve (Hamilton Basin), and Whangamarino Wetland (Lower Waikato)[4]. These wetlands support important ecosystem functions, including water storage and regulation that moderates flooding and drought, while peat-forming systems act as long-term stores of organic carbon (Denyer and Robertson 2016; O'Leary et al. 2025). They also support unique biodiversity and hold cultural significance for Māori communities, providing mahinga kai and other resources (Pawson and Brooking 2013).

[1] The extent of Organic Soils in the Waikato is the area calculated using a combination of S-Map and the Fundamental Soils layer (FSL) where S-Map was unavailable (84,000 ha). This area differs to the area in Pronger et al. 2022 (89,000 ha) because a later version of S-Map was used (after the August 2022 update, where changes to the Waikato region were made - https://smap.landcareresearch.co.nz/support/release-notes).

[2] Greenhouse gas emissions are predominantly carbon-based (carbon dioxide, methane, dissolved organic carbon), however, nitrous oxide can be produced from wet Organic Soils in high nutrient systems (largely caused by fertiliser application on high-production farmland).

[3] Gley Soils may occur in similar position in the landscape as Organic Soils (low-lying flats and valleys) and are waterlogged for part or all of the year, but organic matter is lower in Gley Soils. To be an Organic Soil the soil needs to contain soil horizons with cumulatively more than 0.3 m organic soil material (having at least 18% organic carbon) within the top 0.6 m of the soil profile.

[4] Kopuatai and Whangamarino are protected RAMSAR sites of international significance.

Organic Soils are vulnerable to the impacts discussed above, but are a valuable environmental, ecological, cultural, and economic resource. It is important to understand the peat resource and the risk factors associated with its degradation and loss. Understanding the characteristics and spatial extent of the peat resource will help understand its vulnerability to ongoing subsidence and climate change, and will support informed decision-making around land management, agricultural practices, and infrastructure development.

Characteristics of the peat resource include peat thickness, surface elevation, spatial extent, carbon content, subsidence rate, and land use. In this study, we focus on thickness (and surface elevation to a lesser extent). When peat thickness is combined with peat extent maps, it helps determine how much peat remains, and alongside subsidence rate data, it can indicate how long that peat is likely to persist. Peat thickness information also contributes to assessing inundation risk when considered with subsidence rate, surface elevation, and sea-level rise data. It plays a key role in estimating carbon stocks, understanding the underlying substratum and historical environment, evaluating risk of loss, and establishing a baseline for monitoring peat loss over time. Up-to-date mapping of peat thickness and extent is essential to reduce uncertainty of the peat resource, which is currently based on outdated data, and could support spatial planning and policy development.

1.2 Project aims and objectives

Given the significance of peat thickness outlined above, we initiated a study to assess peat thickness across the Waikato region where Organic Soils were identified. To guide our approach and select measurement locations, we drew on historic peat thickness maps developed for "A Survey of New Zealand Peat Resources" completed by Davoren (1978). Their fieldwork was undertaken between November 1976 and March 1977 and included mapping peat boundaries, peat thickness probing, identifying plant remains within the peat, and characterising the material beneath the peat. The resulting maps have since remained the principal regional reference for peat thickness distribution. However, peat thickness and peatland extent have changed since the Davoren survey as a result of ongoing peat subsidence and land-use change. An updated assessment is therefore required to improve understanding of the contemporary peat resource and provide a consistent regional dataset for comparison across peatlands. This study provides the most comprehensive regional assessment of Waikato peat thickness currently available and represents the first application of a consistent regional-scale regression kriging approach to peat thickness mapping in New Zealand.

The aim of this study was to develop an updated regional inventory of peat thickness across Waikato peatlands using transparent and reproducible field and spatial modelling methods. To achieve this aim, the objectives were to:

1. Identify historic peat thickness measurement sites, and peatlands, to be resurveyed using available land use and soil spatial layers.
2. Collect peat thickness and supporting information (e.g. land cover, von Post humification, and subsurface material type) using manual peat probing and soil sampling techniques.
3. Collect surface elevation information using RTK GNSS (Real-Time Kinetic Global Navigation Satellite System) survey equipment[5]. To be used as a baseline to update peat thickness in the future with the remeasurement of surface elevation.

[5] RTK GNSS = a satellite-based high precision positioning technique that uses real-time signals from a reference station to achieve centimetre-level accuracy.

4. Interpolate measured peat thickness information, and peat thickness information from other sources, into spatial maps showing contour lines of peat thickness for each surveyed peatland and develop cross sections of peatlands where possible.
5. Evaluate the methods used to achieve the above objectives with respect to use in future surveys.

2 Methodology

2.1 Site selection for field survey

Ten major peatlands within the Waikato region, including Moanatuatua, Rukuhia, Komakorau, Orini, Hauraki, Hoe o Tainui, Ohote, Ohinewai, Kainui, and Te Mimiha (Figure 1)[6], were surveyed in 1976 as part of a nation-wide peat survey published by Davoren (1978). These ten peatlands were resurveyed by four field assistants working in pairs over a six-month period (December 2022–July 2023). In addition to the revisited thickness sites, data from earlier historic studies were also incorporated in this analysis; these included previous measurements from Moanatuatua, Rukuhia, and Hauraki, as well as data from Huntly and Lower Waikato peat deposits.

[6] For simplicity, the terms peatland and bog are used generically in this report to refer to all the peat-forming systems surveyed. This usage is not intended to imply that all sites are bogs in the strict wetland-classification sense, as some systems comprise a mixture of bog, fen, swamp, and other wetland types (e.g. Whangamarino).

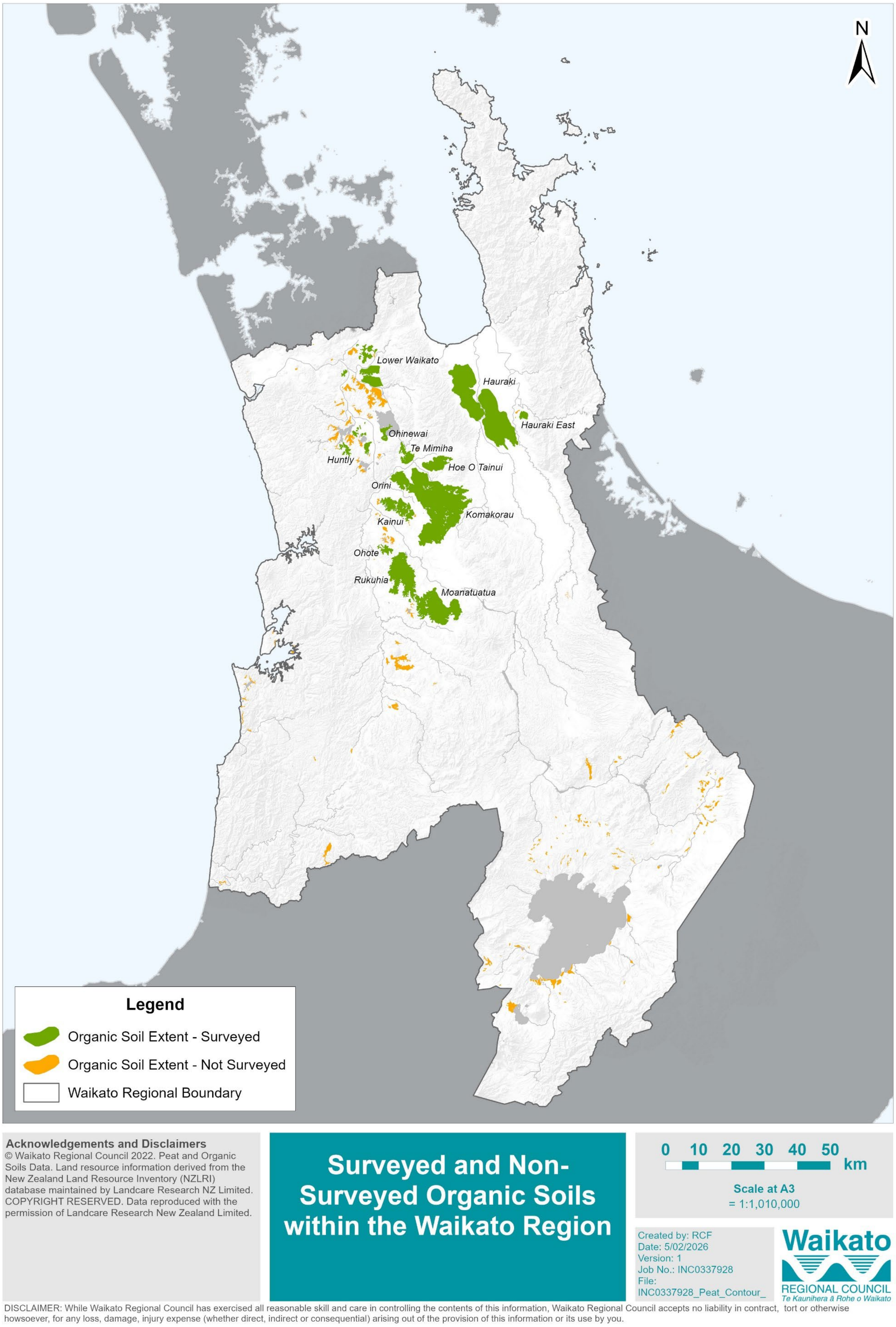

Figure 1. Extent of surveyed (green) and non-surveyed (orange) peatlands in the Waikato region as mapped by S-Map online data updated in August 2022.

The raw data for peat thickness and original site location coordinates from the Davoren (1978) survey have been lost, with only the published contour maps with dots marking site location remaining (Figure 2). Hard copy Waikato maps from Davoren (1978) were georeferenced and digitised in 2017 using ArcMap (R. Glass & K. Jones, pers. comms., December 2022) (Figure 3). For each historic measurement site, New Zealand Transverse Mercator (NZTM) 2000 location was derived, allowing the address and landowner contact details to be sourced from internal Waikato Regional Council (WRC) property spatial layers and Agribase (AsureQuality Ltd. 2022). In the Waikato region, the original Davoren (1978) thickness measurement site totalled over 900, at an average density of about 1.5 sites per km^2. Of these, approximately 80 were on intact peat wetlands or located on Department of Conservation (DOC) reserves and council-owned land and about 50 (of the 80) were inaccessible for this survey. Approximately 800 sites were visited.

To support surveying, property-specific maps showing the location of historic peat thickness measurement sites were interpolated from the Davoren (1978) contours. Although interpolated values do not provide the actual thickness measured during the 1976 survey, each site is a good estimate based on the location of the contours. This provided field surveyors with an indication of historic thickness at the sample location.

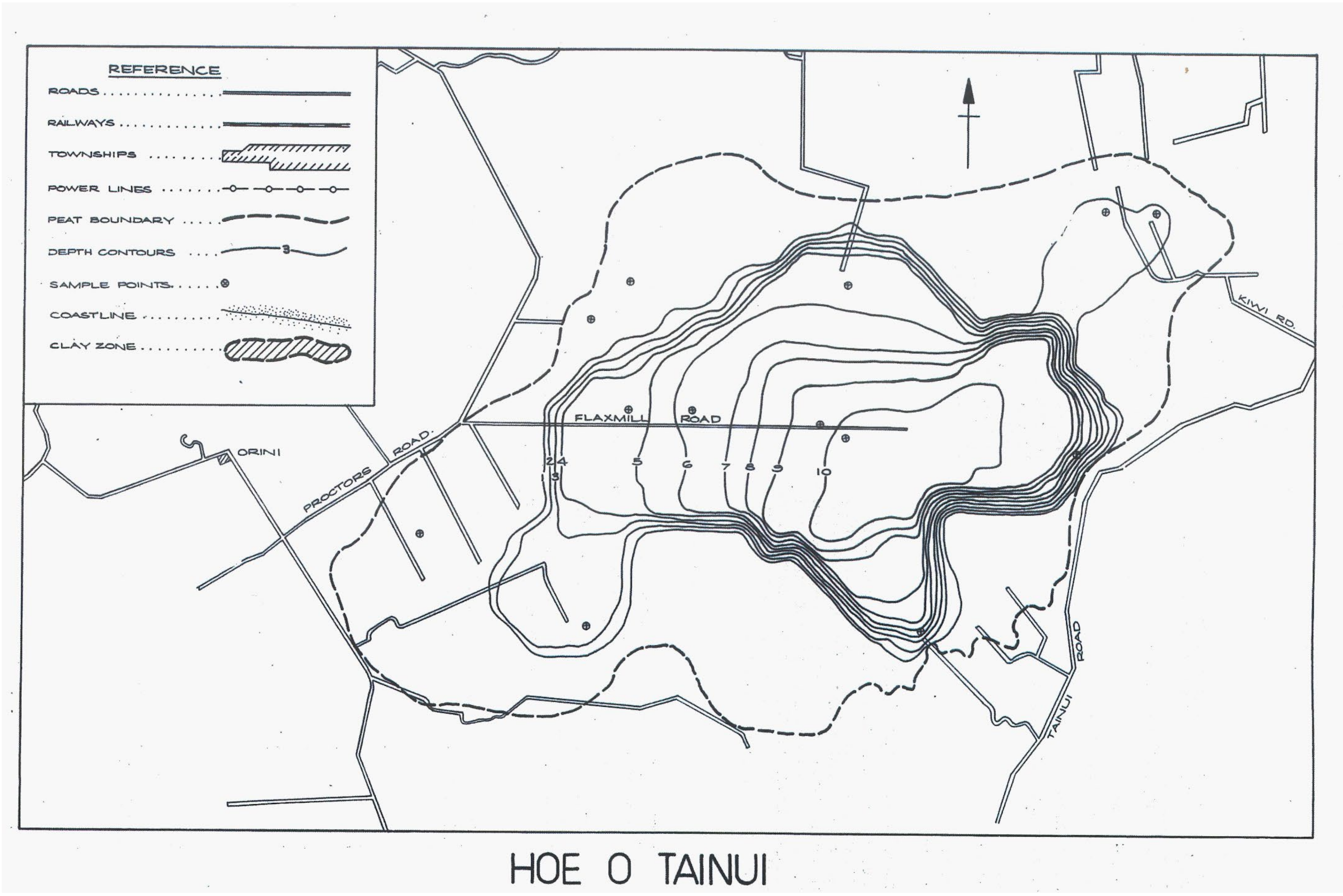

Figure 2. Original peat thickness contour maps of Hoe o Tainui bog as presented in Davoren (1978).

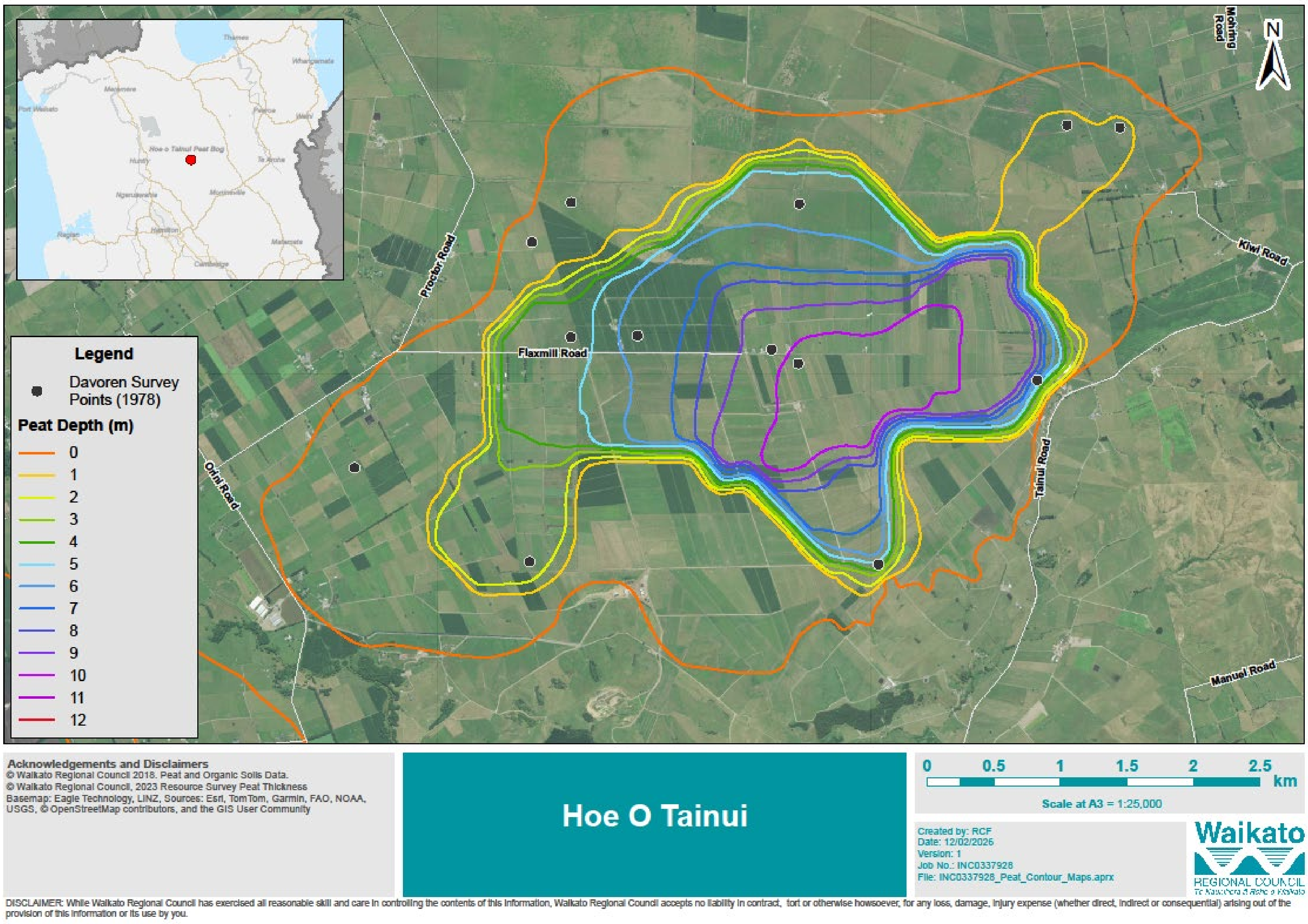

Figure 3. Orthorectified, digitised map of peat contours (coloured lines) and measured sites (black dots) of Hoe o Tainui bog based on the information in Davoren (1978), also displayed in Figure 2.

2.2 Survey design

2.2.1 Peat thickness probing

The peat thickness probing design used in this survey was adapted from Pronger et al. (2013). Each probing point was centred on the NZTM coordinates from the historic peat thickness measurement from Davoren (1978). In addition to these, a further four points perpendicular to each other, and 3 metres from the historic centre point, were probed (Figure 4). These four additional probing points were located: north, east, south, and west of the historic centre point.

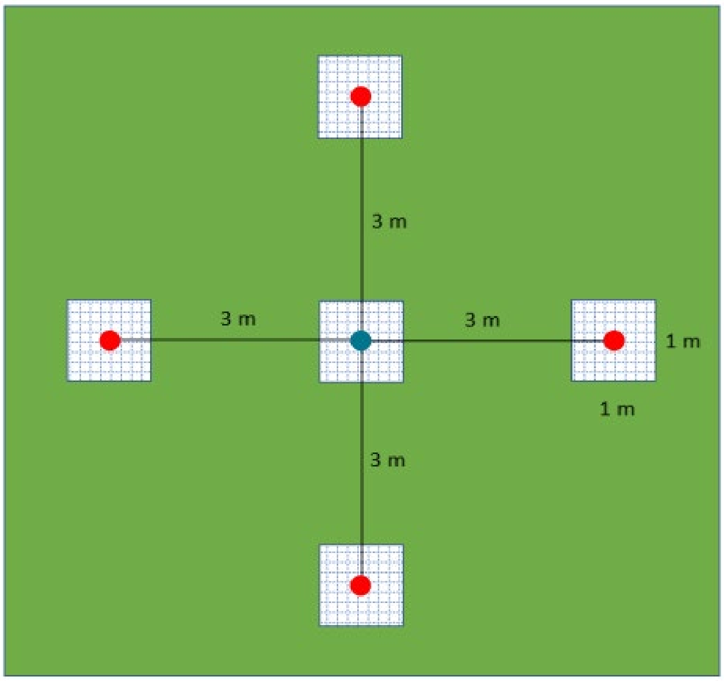

Figure 4. Layout of the peat thickness probing points and the RTK GNSS surface survey at each site. The blue point is centred on the historic probing location from Davoren (1978) and the four red points were probed and surveyed in addition to the historic point. The hatched areas show the five 1 m^2 patches around the manual probing points that were surveyed for surface elevation at 25 points per m^2.

2.2.2 Surface elevation

Prior to peat thickness probing, surface elevation measurements were collected using Global Positioning System (GPS) Real-Time Kinematic Global Navigation Satellite System (RTK GNSS) survey equipment. This included a:

i) Trimble R10 or R8 GNSS receiver,
ii) Trimble TSC5 controller, and
iii) 2 m telescopic survey staff, with a flat wide-base topo-shoe and controller mounts.

The surface elevation sampling design followed the same pattern as described for peat thickness probing (Figure 4). An Observed Control Point (OCP) was taken at the centre of the sampling site to record site location, and a Topographic Point (TOPO) was collected for all other surface elevation measurements. The surface elevation measurements were completed before probing to avoid any ground surface disturbance. A 1 m^2 boundary marker was placed around the centre point and the patch was surveyed at 25 points per m^2, the north, south, east and west patches were completed after that (totalling 125 points measured across the five sample squares at each site).

Undertaking surface elevation measurements at each site provides a baseline measurement for future surveys and eliminates the need to undertake peat thickness probing in the future. When surface elevation is resurveyed in the future, the change in peat surface elevation can be combined with peat thickness observed during this survey to determine the change in peat thickness.

2.3 Field measurement methods

2.3.1 Peat identification

Presence of peat was initially determined by digging a small hole to 60 cm depth and observing if cumulatively there was at least 30 cm of dark, peaty layers (Hewitt 2010). If there was some doubt about the level of organic matter in the observed material (e.g., it was not dark brown/black and therefore did not appear to be peat), a sample was taken to the laboratory to verify whether it met the criteria for Organic Soils under the New Zealand Soil Classification (NZSC) (Hewitt 2010) which is:

"Soils that have horizons that consist of organic soil material (including soils that have skeletal layers in which the matrix of the gravel consists of organic soil material) that within 60 cm of the soil surface are either

1. *30 cm or more thick (cumulative) and are entirely formed from peat or other organic soil materials that have accumulated under wet conditions (they are saturated with water for at least 30 consecutive days in most years, or have been artificially drained) (O horizons), or*
2. *40 cm or more thick and are formed from partly decomposed or well decomposed litter (F and H horizons)"*

Diagnostically, organic soil material (Hewitt 2010) must normally contain at least 18% soil carbon (approximately 30% organic matter)[7] but may also be defined by colour, weight loss on drying or ignition, and fibre content (Milne et al. 1995; Hewitt 2010).

Sampling and determining peat presence in the field was up to the discretion of the surveyor. Digging a 60 cm hole was also useful in determining whether the site had been reworked in some way (e.g., fill added on top near a roadside or new building). This also meant that only peats that could be observed within 60 cm of the soil surface were included in the survey.

2.3.2 Probe methods

Manual peat thickness probing at each location involved sampling at five points (as described in section 2.2.1), starting with the removal of a surface clod and loosening the mineralised peat beneath using a spade. At the central point, a hole 60 cm deep was dug to observe peat characteristics (see above).

For sites with peat thickness greater than 1 m, a 20 mm diameter stainless steel peat probe with a 150 mm long auger-type drill bit was pushed through the peat until a change in resistance occurred and the firm mineral base was struck, additional rods of known length were added as needed. Often the subsurface texture was felt through the peat probe. This also gave an

[7] Organic Carbon (OC) represents the carbon component of the total organic material (or Total Carbon). OC in this study was measured using Dumas combustion analysis. Organic Matter (OM) was estimated from measured OC using a conversion factor of 1.72 (i.e. OM = 1.72 × OC), consistent with the laboratory protocol applied to samples reported in section 2.3.1 and Appendix J. While this factor is widely used, it is an approximation and has been subject to critique due to variability in the OC:OM relationship across soil types (Pribyl 2010; Navarro et al. 2020; Minasny et al. 2024).

indication that the base of the peat had been struck. Once the subsurface base of the peat was reached, the length of rod aboveground was measured. The rods were removed and counted to determine the total inserted length. Peat thickness was calculated by subtracting the aboveground rod length from the total inserted length. If the auger tip sampled mineral material below the peat, the length of collected material is subtracted from the total thickness. The material beneath the peat was recorded and photographed (for more details on the probing method, see Appendix A – Peat thickness probing methods – extended field guide).

A Dutch auger was used to measure thickness to 1 metre, these sites were identified based on peatland sites reported in Davoren (1978) with a thickness of <2 m. Field Assistants found using the Dutch auger end-piece was easier and more effective than the peat probes drill-bit end-piece, for collecting and determining the base layer at these shallow depths.

There were some challenges using the peat probe for sites with peat greater than 1 metre thick including, identifying the exact transition to mineral material (e.g., where fine/fluid silts often rub off the drill bit during extraction[8] or when detecting thin subsurface silt layers between peat layers), and where impenetrable buried wood obstructed the insertion of the probe/drill throughout the profile (e.g., at Rukuhia). Where obstructions were met or there was uncertainty about base detection, the point was attempted again (up to 5 times)[9] within roughly a 1 metre radius of the original point. If none of these attempts were successful, the point was abandoned and the average was taken from the other successfully sampled points from within the site.[10]

2.3.3 Peat probe extraction

Two methods of probe extraction were employed when obstructions were met or where suction friction was too strong to safely remove the probe. The two methods are shown in Figure 5 and included:

- Lever jack — Uses a pivoting fulcrum and lever arm to provide mechanical advantage for vertical lift, reducing operator strain in high-suction or obstructed holes.
- Pulley system — A tripod-mounted block and tackle pulley connects to a customised probe handle; the hook engages the handle and the pulley lifts directly upward toward the tripod apex for smooth, controlled extraction.

These tools were important for survey continuity, but both had limitations including portability and the load capacity (needs to be of good quality because the heavy-equipment failure would be high risk to operators). Originally, a boat winch was used in place of the block and tackle pulley, however, there was concerns about the load-bearing capacity and tensile rating of the boat winch, so this was replaced.

[8] Fine silts and materials tend to rub off the drill-bit upon removal from the peat, making them difficult to detect, whereas sand or clay is more easily identified by texture or adhesion.
[9] Points were attempted up to a maximum of five times before deciding to stop for the sake of time and health & safety.
[10] In some cases, there was only one successful point and therefore only one point was used in the average. The success rate is presented in the results.

Lever-jack	Pulley
	

Figure 5. Photos of setup lever jack (left) and pulley system (right) used for extracting stuck peat probes. The lever jack could also lift the peat probe at the handle.

2.3.4 Peat surface elevation

2.3.4.1 Site measurements

To measure surface elevation at each manual probing point, a Trimble R8 or R10 RTK GNSS receiver, attached to a telescopic survey pole and managed with a Trimble TSC5 controller, was remotely connected to the local network of continuously operating reference stations (CORs) as part of the Trimble VRS Now network. Setup instructions for the survey system and network connection are provided in Appendix B – Surface elevation measurement instructions – extended field guide. Once connected, five 1 m² patches per site, each containing 25 measurement points per patch (as mentioned in section 2.2.2) were surveyed for surface elevation. To ensure accurate surface elevation measurement, the survey staff was held perpendicular to the ground, using the level bubble for guidance (Figure 6) and a small flat wide base topo-shoe was attached to end of the survey pole to prevent the tip of the survey staff from sinking into the soil.

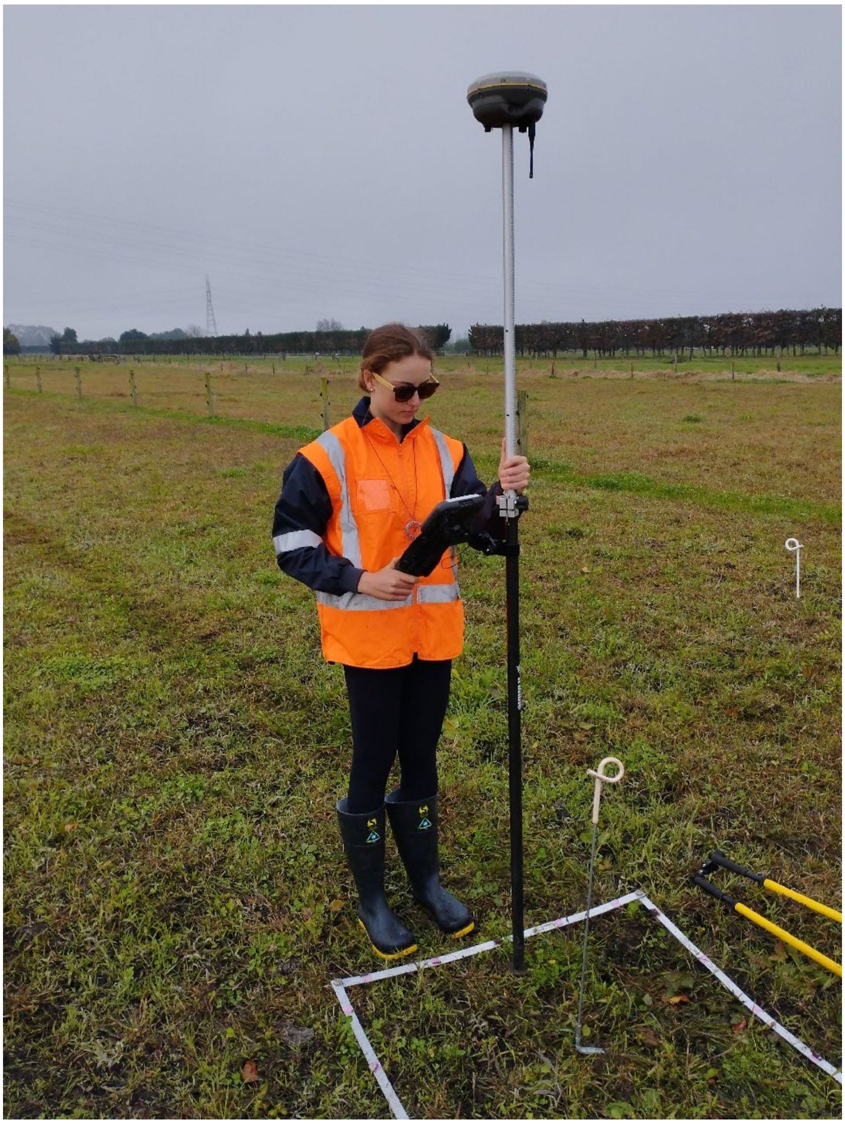

Figure 6. RTK GNSS setup and measurement within 1 m² square.

To ensure accuracy of the surveying operation, a daily OCP and TOPO reference measurement was taken at a local geodetic marker near the area being surveyed, at either the start or end of the day (or both). The maximum tolerance for surveying was +/- 20 mm from the reference elevation recorded at the geodetic marker.

2.3.5 Field and peat conditions

The field work was undertaken between Dec 2022 and June 2023. Site information was recorded in Field Maps (Esri Field Maps, version 2023.1, Esri Inc.) while in the field, which automatically uploads to ArcGIS Online (AGOL)[11]. Field Maps was also used to record the sample location[12], assisting with future relocation. Alongside thickness measurements, the following ancillary information was recorded in field:

- **Sample location**
- **Weather conditions**

[11] Field Maps is an application allowing field data to be collected and directly synced to maps and datasets stored in AGOL. AGOL is a cloud-based GIS platform for mapping, analysis, and data sharing.

[12] Coordinate accuracy of Field Maps app is reliant on cell phone's coordinate accuracy.

- **Peat Humification Index:** Assessed using the von Post scale (10-point visual method) to estimate the degree of peat decomposition, based on physical and chemical properties (Appendix C – Von Post index).
- **Organic Carbon Soil Sampling:** Samples were taken when the organic matter content was uncertain (see section 2.3.1). The decision to sample and the depth of the sample was recorded in the site information.
- **Water Table Depth:** Measured in the field based on visual observations at the time of sampling.
- **Vegetation type**
- **Land Use and Management:** Current land use/cover was noted during sampling. Sites under maize cultivation were avoided and revisited post-harvest. Where surface recontouring (e.g., hump and hollow) was evident, this was also noted due to its potential impact on peat characteristics (e.g., thickness, subsidence, carbon content, and hydrology).[13]
- **Site Adjustments:** Thickness measurement points located within 10 metres of drains or obstructed by infrastructure (e.g., roads, races, buildings) were relocated to nearby suitable locations.
- **Any further comments**: Including description of soil profile for shallow sites, reason for site adjustments or for site avoidance, and any further information deemed relevant by the surveyor.

2.4 Data processing

2.4.1 Data download/handling

At least once weekly, peat thickness measurements and ancillary site information was downloaded from AGOL into an Excel spreadsheet. Surface elevation data was downloaded from the survey unit controller and saved into a spreadsheet.

To clean the peat thickness data, we removed any duplicate entries and made any necessary adjustments to the points based on the comments provided. The organic matter sample results were analysed against peat thickness; if a topsoil sample was less than 18% organic carbon, and the recorded peat thickness exceeded 0.3 metres, the thickness of the peat deposit should be defaulted to less than 0.3 metres (the threshold for Organic Soil classification in Hewitt (2010)) to reflect that the site is not a peat soil. The cleaned thickness data spreadsheets are available as *Supplementary material S1* (see Appendix D – Supplementary material index).

To clean the surface elevation data, peat survey measurements were compiled and summarised as provided in *Supplementary material S2*. Northing and Easting coordinates (NZTM) for each site were sourced from OCP dataset values, while elevation (NZVD 2016) was derived by averaging TOPO measurements taken at each of the five points (centre, north, east, south, and west). This process was carried out separately for measurements collected using R8 and R10 receiver units because only one unit was used at each measurement site and corresponding geodetic marker. Calculation steps were checked to ensure formulas referenced the correct source data. This process identified and corrected errors, including any mistakes in formulas across worksheets or inconsistencies in recorded data. Differences between measured and known values for geodetic markers were then used to estimate measurement uncertainty and

[13] Although hump and hollow relief can introduce local variability in peat thickness, this was not directly applied to the results, because the work was paddock to peatland scale, rather than microtopographic or ecological plot-scale. This also maintains comparability to other historic Waikato peat surveys, which did not stratify measurements by land contouring.

the difference in these values was analysed to show the frequency of different ranges of uncertainty. Geodetic marker measurements are not included in *Supplementary material S2*.

2.4.2 Additional datasets

Alongside the ~800 sites visited in 2023 for this study, additional data sources include the original regional peat survey conducted in 1976 for undisturbed peatland areas, historical well records, and targeted investigations at Moanatuatua (2012, 2019), Hauraki (2012), Rukuhia (2012), Lower Waikato and Huntly (2012), and Kopuatai (2024) (Table 1). These datasets were combined to improve spatial coverage and enhance model reliability across bogs of varying size and complexity.

Table 1. Peat thickness surveys in the Waikato region (data used for this study).

Year of survey	Area surveyed (number of measurement sites)	Source	Comments
1976	DOC & council owned land (intact sites) – Hauraki (69) and Moanatuatua (2)	(Davoren 1978)	The 1978 Davoren study published results for intact peat sites (e.g., Kopuatai Peat Dome and Moanatuatua peat reserve*). These sites are assumed to have remained intact since initial thickness probing, so we kept the same estimated thickness**. Subsidence was not calculated for these sites based on the assumption that they would not be subsiding in an intact state***.
2012	Lower Waikato (52) & Huntly (266)	(Palmer and Hainsworth 2012)	The Lower Waikato study was undertaken between January and June of 2012 by Landcare Research at the request of WRC to survey peatlands associated with selected pump stations in the North Waikato. Site locations were transects or grids determined by a desktop survey of the areas of interest.
2012	Hauraki (80)	(Thakur 2015)	The 2012 catchment survey is an unpublished survey of the Muggeridges catchment for a pumpstation upgrade proposal.
2012	Rukuhia (60), Hauraki (90), Moanatuatua (60)	(Pronger et al. 2014)	The Pronger et al. 2014 survey was undertaken to calculate subsidence rates for drained agricultural peatlands in Hauraki, Moanatuatua, and Rukuhia. Peat survey transects in the peatland areas were originally set out by land drainage engineers in the early 1920s. These transects were first resurveyed in 2002 (Moanatuatua), 2003 (Hauraki), and 2004 (Rukuhia) to determine subsidence in these drained peatlands and published as technical reports see; Mckenzie & McLeod 2004, McLeod et al. 2003, Fitzgerald & McLeod 2005). A decade later, sites were surveyed and the difference between the thicknesses over this period was used to calculate contemporary subsidence rate for each area.

2019	Moanatuatua (24)	(Pronger et al. 2020)	The 2019 survey by Pronger et al. was undertaken by Landcare Research on behalf of WRC and resampled a subset of Davoren (1978) sites at Moanatuatua peatland. This work was completed to assess the feasibility of using the Davoren (1978) measurement sites for future subsidence monitoring.
2024	Kopuatai (2)	A. Wheatley-Wilson, unpublished data, 2024	Opportunistic survey at Kopuatai Peat Dome undertaken by WRC for another project. Sites were located within 40 metres of each other.
1960 - 2022	Komakorau (78), Hoe o Tainui (6), Ohinewai (5), Rukuhia (12), Moanatuatua (2) Hauraki (17) Orini (6) Ohote (1)	(Te Uru Kahika)	The Wells Aotearoa NZ dataset is a publicly accessible map and search tool of well installation locations across the country (for regions currently involved in the initiative). Lithological data describes the stratigraphic layering from surface soil, sediment, and rock. Wells that intersected with the Organic Soil extent in the Waikato region were queried for peat surface layers within 60 cm of the surface. Where the site met specific criteria (Appendix E – Borehole peat thickness data and conditions), the thickness of peat recorded was used.

* Measured sites from the 1976 survey were also found in Whangamarino but had no thickness estimate associated with them.

** The estimated thickness is that calculated from digitising site locations from historic maps and using the contours to estimate thickness.

*** In this study, we assumed there was no change in thickness for Moanatuatua peatland, however it may be affected by subsidence of surrounding farmland, considering it is a small remaining intact area.

2.4.3 Calculating average thickness & subsidence

All datasets contained the following key information: bog name, field comments, site coordinates, site visit date, and peat thickness. Mean peat thickness was calculated for each site to summarise the data. The 5-point sampling design (section 2.2.1) was intended to provide quality assurance and a representative site-scale estimate of peat thickness so measurements were averaged to a single value prior to spatial modelling. This pragmatic approach was broadly consistent with the Davoren (1978) sites, which were originally established for contour mapping rather than geostatistical modelling, although averaging the five measurements into a single site value removes information on local variability over distances of a few metres.

As the datasets span multiple years, each thickness measurement was adjusted to a predicted 2023 thickness using contemporary subsidence rates reported by Pronger et al. (2014). Pronger et al. (2014) reports historic and contemporary subsidence rates for Moanatuatua, Rukuhia, and Hauraki based on differences in thicknesses measured between the 1920's and 2000's (historic) and the 2000's and 2012 (contemporary). Contemporary and historic rates were also estimated for other Waikato peatlands based on the average subsidence rate of all three bogs.

2.4.4 Peat thickness and depth to mineral subsurface

Peat thickness is the vertical thickness of the peat layer, measured from the top of the identifiable peat to the subsurface peat–mineral boundary (Figure 7A). In the international peatland literature and historic Waikato studies, the terms peat depth and peat thickness are sometimes used interchangeably to describe the vertical extent of the peat deposit. However, in this study the term peat thickness will be used.

In the Waikato region where the peat is thick (>1 m), most historic studies (e.g., Davoren 1978; McLeod et al. 2003; McKenzie and McLeod 2004; Fitzgerald and McLeod 2005; Pronger 2013; Pronger et al. 2014) have measured peat thickness by pushing a thin diameter steel probe with an auger-type drill bit through the peat until resistance is felt and the firm subsurface mineral material is struck. When the probe is retrieved the interface between the peat and subsurface mineral material is observed on the drill bit to confirm the base of the peat has been struck. Where the peat is thin (<1 m) a soil pit or Dutch Auger is used to determine peat thickness, whereby the interface between the base of the peat and firm subsurface material is observed. However, the Lower Waikato Catchment Survey by Palmer and Hainsworth (2012), introduced a new approach by differentiating between true peat thickness and depth to a firm underlying mineral substrate where necessary (Figure 7B). In Palmer and Hainsworth (2012) peat *thickness* was determined traditionally where possible. However, due to the fluid silts and clays underlying many peatlands in the Lower Waikato catchment management zone the interface between the base of the peat and mineral subsurface material was hard to detect. In these circumstances, Palmer & Hainsworth (2012) felt that determining peat thickness with the probe method was not accurate and they reported "*depth to firm mineral substratum",* where the probe-measured vertical distance from the ground surface to the first firm mineral layer (Figure 7C).

In our study we adopted the same field approach as Pronger (2013) and Pronger et al. (2014), using a Dutch auger to assess peat down to 1 m and a peat probe for thicknesses greater than 1 m. Unlike Palmer & Hainsworth (2012), we report all measurements as peat thickness, as the peat in our areas of interest typically sits directly on firm mineral material and the peat–mineral interface can be clearly identified. Previous surveys (e.g. Pronger et al. 2014) in these locations have not encountered the soft, fluid silts or clays that prevented reliable interface detection in other parts of the region (e.g., peatlands near Huntly), and our own field observations confirmed that underlying clays, silts, or sands provided a distinct resistance change detectable by auger or probe. Although, some softer subsurface sediments were encountered in the Hauraki peatlands, the peat–mineral interface was still able to be determined. As a result, the measured vertical distance to the peat–mineral interface could be treated as true peat thickness at all sites.

Where we included data from other surveys that reported true peat thickness (i.e., where the peat–mineral interface was clearly identifiable) in the mapping of peat thickness, the values were used directly. In contrast, the data from Palmer & Hainsworth (2012), who reported depth to firm mineral substratum (particularly for the Huntly peatlands where the peat base could not be confidently identified) were included in our results with the caveat that some of the values represent depth to firm mineral substratum and not true peat thickness.

While *peat depth* is commonly used in other studies synonymously with thickness, in this study it is only used to describe the depth of the probe point or another specific reference/measurement point (e.g., depth to a buried peat layer).

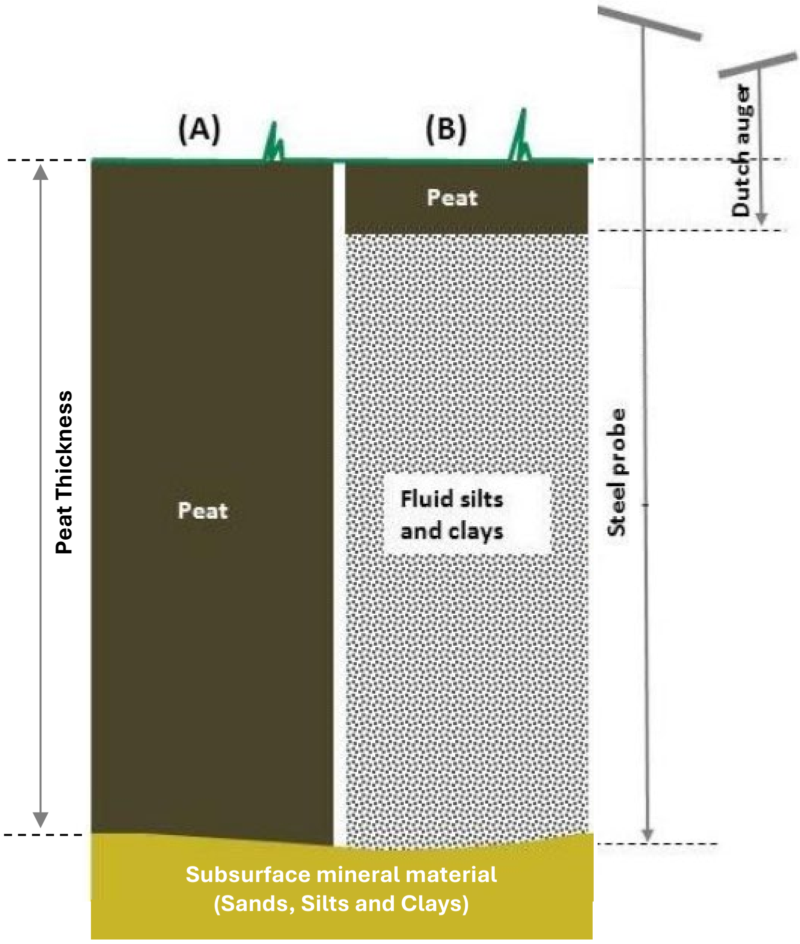

Figure 7. Schematic showing the difference between peat thickness and depth to firm mineral substratum measurement approaches. (A) shows the true peat thickness, defined as the vertical distance from the ground surface to the clearly identifiable peat–mineral interface where peat overlies firm mineral material; this represents peat thickness as used in this study. (B) illustrates conditions where peat overlies soft, fluid silts and clays, making the peat–mineral interface difficult to detect using probing or augering at depth (>1 m), and therefore preventing reliable determination of true peat thickness. In these cases, measurement of depth to firm mineral substratum with a steel probe records the vertical distance from the ground surface to the first firm mineral layer beneath peat and overlying soft/fluid sediments; this represents depth to firm substrate rather than true peat thickness. However, where peat thickness is <1 m in these settings, augering can still be used to identify the peat–mineral interface and determine true peat thickness. Adapted from Palmer & Hainsworth (2012).

2.5 Creating contours using geospatial methods

2.5.1 Extent & boundary

The most up-to-date map of Organic Soils in New Zealand is S-Map, which utilises updated digital soil mapping techniques and offers higher quality data (Manaaki Whenua - Landcare Research 2022). Where appropriate, S-Map was used as the boundary line depicting the spatial extent of the Organic Soils in this survey. S-Map also includes small geographic features mapped within the peat boundary such as hills and streams.

In some cases, there were peat thickness sites measuring more than 0.3 m located outside of the S-Map boundary and non-peat (<0.3 m) located inside the S-Map boundary. Due to these discrepancies and to constrain the contours, we used several available methods to recreate the Organic Soil boundaries of bogs visited in this survey. We worked through a process of inclusion/exclusion based on available soil maps and where no maps were available – an extension of the outer boundary by buffer, then further refinement based on topography and surrounding sites (informed subjectivity). S-Map information was prioritised first. Where the S-Map boundary had instances of the above (peat sites located outside or non-peat sites located within the boundary), the next option was either the Fundamental Soils layer (FSL) or the 1978 Davoren outer boundary line. The FSL, mapped between 1940 and 1980 at a 1:50,000 scale, provides complete coverage but is being replaced by S-Map. The Davoren outer boundary line was created in the 1978 survey depicting the spatial extent of the Organic Soil boundary. It is unclear based on the written methods what technique they used to estimate the lines, but it was likely informed by thickness sites from the survey, field observations, and by known geological/geographical features. The FSL and Davoren lines were equally favoured and chosen based on the smallest polygon encapsulating the area (closest to the S-Map boundary, while encapsulating the site). Larger polygons that extended well beyond the S-Map boundary were treated with caution and the buffer method was subjectively chosen instead. To select the most appropriate line, all relevant Organic Soil boundary layers (FSL, Davoren, and S-Map) were mapped and each line was individualised so it could be deleted in favour of keeping the most appropriate boundary line. For further details and visual descriptions of this method, see Appendix F – Boundary methods extended.

If neither the FSL nor Davoren lines were deemed to be appropriate, we extended the boundary by applying a circular buffer around the site until the original boundary line was intersected, then manually shifted the boundary to follow the buffer line. Buffer boundary methods are described more fully in Appendix F, in section 12.2.

The boundary line is not a true ‘0 metre’ thickness line for peat but is instead assumed to represent a thickness of 0.3 metres. This aligns with the S-Map criteria for defining Organic Soils by thickness, as outlined by Hewitt (2010). Due to the absence of more precise thickness data, the same assumption was applied to both the FSL and Davoren boundaries[14].

Alongside all of the above options, we observed vegetation and other structures from aerial imagery and surface elevation using 2021 LiDAR digital elevation models (DEMs) for the Waikato region to provide insight into the likelihood of the site being in a particular location (e.g., sites were removed if located on a slope). Natural geographic features such as rivers and streams, as well as artificial/built features such as quarries and towns also informed changes to the boundary.

For bogs under the same name that have different geomorphic units or some sort of geological boundary separating the units (e.g., rivers, hills) the boundary lines between the units were included to split the bog into sections for creating contours. Otherwise, the contour model would try to extend beyond the S-Map boundary and link the other units. This was relevant for Hauraki/Kopuatai which is split by the Piako river and for the Lower Waikato and Huntly areas surveyed in 2012. We used the same peatland naming conventions as described in the 2012 survey (Palmer and Hainsworth 2012).

[14] Davoren (1978) states “the peat boundary […] signifies the boundary between the raw peat, whatever its classification, and any mineralised or oxidised peat which may surround the swamp” and the introductory chapters suggest that in many cases the peat was mineralised to 0.2–0.3 m, suggesting that this thickness might be the limit for Organic Soils classification.

Establishing a clear boundary around each bog was a critical step before generating contour lines. Without these boundaries, the kriging[15] model would have extended contour predictions into areas where peat is unlikely to occur, creating misleading results. The boundaries also provided additional information used in the kriging as it was assumed that a peat depth of 0.3 m occurred at the boundary (based on the definition of Hewitt 2010). The completed boundary provided a spatial constraint, ensuring that contour lines remained within the plausible extent of Organic Soils and reflected realistic spatial patterns. The finalised boundary line was converted into points every 200 m (measuring the lowest defined Organic Soil thickness = 0.3 m) to download as a .csv file to be imported into R.

2.5.2 Spatial modelling of peat thickness into contour maps

We used trend surface analysis followed by residual kriging[16] within R to produce representative contours for peat thickness. These analyses were performed using R version 4.5.2 (R Core Team 2025). We explored a few different contour creation (interpolation) methods including Inverse Distance Weighting (IDW)[17] and Empirical Bayesian Kriging (EBK)[18]. IDW was sensitive to clustering and outliers and is more suited for evenly distributed data, so tended to create a bullseye effect when used on our dataset (Munyati and Sinthumule 2021). EBK was explored but lacked transparency in variogram[19] selection. Ordinary kriging, specifically regression kriging, was the favoured method because it can use a limited set of sampled sites to estimate thickness values over a continuous spatial field and is recommended for soils and landscapes (Koganti et al. 2023). A spline model[20] was used to capture the trend fitted using the R gam function, although a quadratic model was also considered. We fitted the trend surface and kriged the residuals from the surface model using the R variogram and krige functions. The final predictions were obtained by summing the trend surface and the kriged residuals. Separate surfaces were fitted for each peat bog. Once complete, contours were imported into ArcGIS Pro from R as a GeoTIFF raster file[21]. Appendix G – Statistical R and ArcGIS methods for creating contours, provides the statistical procedures, variogram fitting methods, model-selection considerations, and other kriging settings used in the interpolation, while the full R script is provided in *Supplementary material S3*.

After the contours were finalised, we edited the contour lines in ArcGIS Pro to fit within the spatial extent of the bog (both outer and inner geographical boundaries (e.g., hills, streams). Our justification for this decision is that peat is not likely to abruptly shift from >1 m to <0.3 m without an incremental decrease in thickness. For further details on this methodology, see Appendix H – Contour adjustment methodology.

2.5.3 Visualisation of peat thickness using cross-sectional profile

Profiles of the depth to the base of the peat (developed from modelled thickness contours) and surface elevation (developed from LiDAR) were used to visualise cross-sectional thickness profiles across transect lines for each bog. The elevation profile was created along a transect

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[15] Kriging = a geostatistical interpolation method that estimates values using spatial autocorrelation, assuming a constant but unknown mean across the study area.

[16] Regression kriging (residual kriging) = a hybrid interpolation method in which a trend is first modelled using explanatory variables, and kriging is then applied to the residuals to account for spatial autocorrelation and improve prediction accuracy.

[17] IDW = an interpolation method that estimates values at unknown locations based on nearby observations, weighted by distance so that closer points have more influence.

[18] EBK = a geostatistical interpolation method that uses repeated simulations to account for uncertainty in the spatial model.

[19] Variogram = a statistical tool that shows how differences between data values increase as the distance between them increases.

[20] Spline model = a deterministic interpolation method that fits a smooth surface through known data points, minimising overall surface curvature to produce a continuous and gently varying surface.

[21] GeoTIFF raster = a georeferenced raster file format in which each pixel contains a data value (e.g., elevation) and is spatially aligned to real-world coordinates.

line across the length of each bog (and along the width for larger bogs). This was undertaken in GIS using the *Stack Profile* tool using both the 2021 LiDAR DEM data and the resulting kriged raster from our measured thickness data (used when creating our contour lines, see section 2.5.2). The measured probe thickness data and the predicted kriged data aligned well ($R^2 = 0.85$), indicating that the model captures a large proportion of the overall variance in peat thickness (Figure 8). However, the spread of the data suggests a slight systematic underestimation of peat depth at greater thicknesses, consistent with biases reported in the international literature (e.g. Adetsu et al. 2024). Despite this tendency, the model provides a robust representation of relative spatial patterns within each bog.

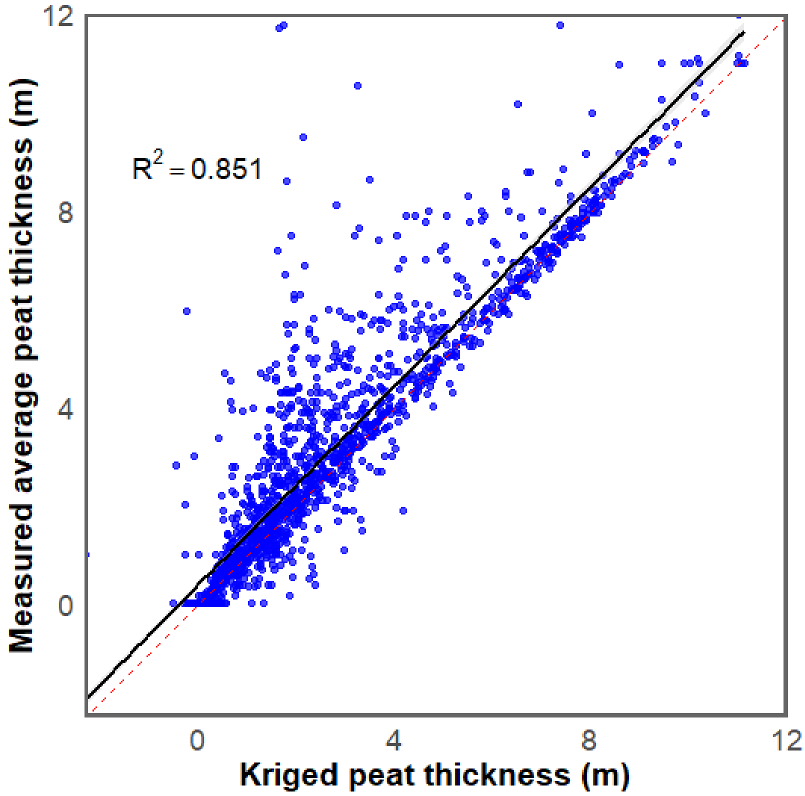


Figure 8. Measured peat thickness versus kriging model predicted thickness.

Surface elevation data were compared with the 2021 LiDAR dataset to validate our collected information. Measured surface elevation and LiDAR grid surface elevation were compared and received an R^2 value over 0.99 (Figure 9). The complete dataset (n ≈ 500 rows) is provided as *Supplementary material S2*. The high R^2 value suggests the two datasets are very similar, so we used the higher resolution 2021 LiDAR DEM raster compared to the measured surface elevation raster created in section 2.5.2 to visualise peat thickness across transects.

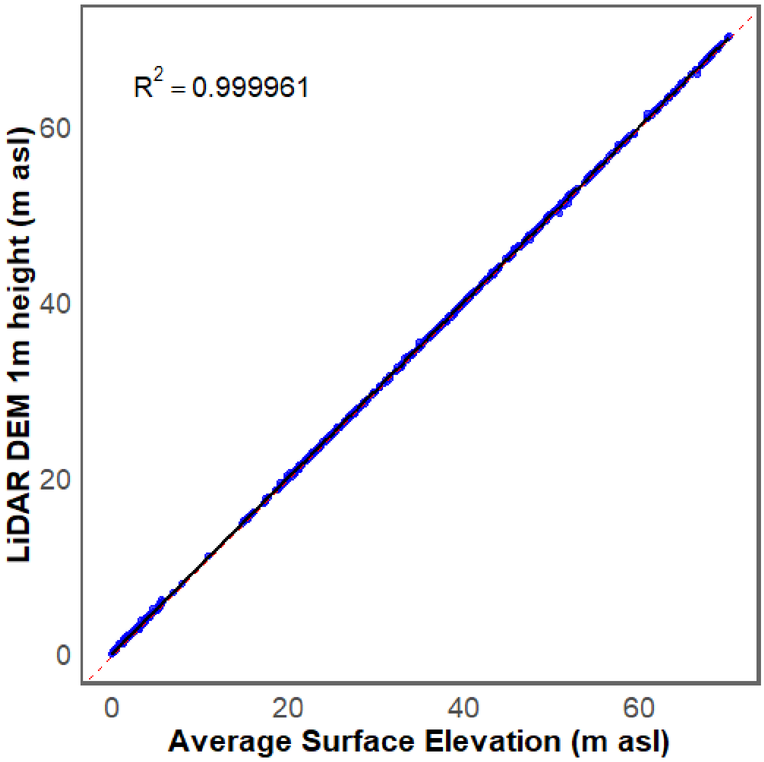


Figure 9. Measured surface elevation (height) versus LiDAR DEM 1 metre grid surface elevation.

2.5.4 Contour map boundary uncertainty and display

The creation of the boundary used to constrain the contours is described in section 2.5.1 and displayed in Appendix F – Boundary methods extended. However, this boundary is not used for the maps displayed in the results because the assumptions used in our methods were an interim approach to dealing with specific cases. While this approach was useful for constraining the contours (which is required for the methodology used for creating the contours), it is not an established method for mapping the extent of Organic Soils and would need further development to be used for that purpose.

Instead, for the boundary displayed in the results, we used a simplified, conservative approach. We primarily used the S-Map boundary and where sites fell outside of this, we utilised the 1978 Davoren outer boundary to mark the 0.3 m outer extent of Organic Soils. Where sites fell outside of both boundaries, we used the buffering method. Where sites less than 0.3 m fell inside of this boundary, we left the site but addressed this by marking the entire area between the 1 m contour line and the conservative S-Map/1978 boundary, as uncertain/low confidence.

2.5.5 Calculating peat bog volume

Peat bog volume was estimated by summing the product of the mapped area within each peat thickness contour and the representative thickness assigned to that contour. Total volume was calculated as the area-weighted sum of all thickness classes (e.g. 100 km^2 × 1 m, 50 km^2 × 2 m, and 10 km^2 × 3 m = 0.23 km^3). For disconnected peatland systems (e.g. Huntly), where multiple discrete bogs within the same area are separated by geological features such as hills or rivers, peat volume was calculated for each bog individually and then summed to derive a total volume for the system.

3 Results

3.1 Peat thickness patterns

Table 2 summarises key information for each bog, including area, estimated peat volume (section 2.5.5), maximum surface elevation, and associated district(s). For example, Hauraki (including Torehape, Hauraki East, and Kopuatai) covers 213.5–243.6 km^2 with an estimated peat volume of 0.7 km^3, while smaller bogs such as Ohote occupy only 5.9–11.2 km^2 with a volume of 0.003 km^3. For bogs with small areas and large volumes (e.g., Te Mimiha), measurements indicated average thickness across the bog is deeper relative to other bogs, thus the volume is high considering the area. Figure 10 supplements the site information presented in Table 2 including key statistics. Note some bogs combined in Table 2 are separated out as seen in the contours presented in the figures listed in Table 2. For further bog information, see Appendix I –Table of bog information.

Table 2. Summary of Waikato peat bog characteristics, including estimated area, approximate peat volume, highest surface elevation, district in which the bog occurs, and corresponding figure references related to each bog in the coming sections.

Bog	Area (km^2)*	Volume (km^3)	Highest point (m asl and coordinates)	Districts	Contour map figure number
Hauraki (includes Hauraki East and Kopuatai)	213.5–243.6	0.7	7.07 m 175.5739452°E 37.4684287°S	Hauraki, Matamata-Piako	Figure 11 Figure 12 Figure 13 Figure 14
Hoe o Tainui	19.8–23	0.05	25.54 m 175.3837309°E 37.5622928°S	Waikato, Matamata-Piako	Figure 15 Figure 16 Figure 17
Huntly	10.7–29.2	0.01	11.13 m 175.1340976°E 37.5297131°S	Waikato	Figure 18
Kainui	23.3–29.5	0.015	31.46 m 175.2895561°E 37.6985162°S	Waikato	Figure 19 Figure 20 Figure 21.
Komakorau	212.6–225.7	0.26	44.38 m 175.4003789°E 37.7269002°S	Waikato, Hamilton Matamata-Piako	Figure 22 Figure 23 Figure 24
Lower Waikato (includes Whangamarino)	36–68.1	0.01	6.23 m 175.1482861°E 37.3171207°S	Waikato	Figure 25
Moanatuatua	84.4–86.8	0.21	71.34 m 175.4110206°E 37.9614533°S	Waipa	Figure 26 Figure 27 Figure 28
Ohinewai	10.4–14.6	0.005	10.99 m 175.1915311°E 37.4993794°S	Waikato	Figure 29
Ohote	5.9–11.2	0.003	35.06 m 175.2307714°E 37.7624876°S	Waikato, Hamilton	Figure 30 Figure 31 Figure 32
Orini	16.4–16.6	0.05	22.37 m 175.2651651°E 37.6061409°S	Waikato	Figure 33 Figure 34 Figure 35
Rukuhia	66.2–66.6	0.21	57.96 m 175.2941123°E 37.8871778°S	Waipa Hamilton	Figure 36 Figure 37 Figure 38
Te Mimiha	9.4–12.6	0.01	24.19 m 175.2772513°E 37.5251469°S	Waikato	Figure 39

* Area is reported as a range based on the areas calculated within the smaller, stricter boundary used to constrain contours (section 2.5.1; lower bound) and within the larger, more conservative boundary displayed in the results (section 2.5.4; upper bound). Peat volume was calculated using the same boundary extents; however, the resulting range in volume was negligible at the km^3 scale and is therefore reported as a single rounded value.

Peat thickness measurements across the Waikato region show substantial variation, both within and among bogs, with maximum thickness measuring more than 11 m in deeper systems including Rukuhia (11.1 m), Moanatuatua (11 m), Kopuatai (12 m), and Te Mimiha (11.8 m). The deepest single probe measurement recorded was 13.1 m at Te Mimiha (averaged to 11.8 m based on two additional measurements at the site). Statistical outliers were detected for

Hauraki, Huntly, Kainui, Komakorau, and Te Mimiha. Outliers were defined as values more than 1.5 times the interquartile range above or below the quartiles, following the standard Tukey boxplot method, and identification was applied separately for each bog. These outliers were retained in the dataset and included in the kriging interpolation to preserve observed local variability.

Across all sites, thickness generally decreased from interior ‘domed’ or elevated zones toward mineral edges, but this pattern varied depending on disturbance history, drainage, and original basin morphology. Of the ~800 measurement sites revisited from the 1978 survey, approximately 200 were classified as non-peat (i.e., no peat present, peat less than 0.3 m thick, or peat with organic carbon content below 18%) (Hewitt 2010) (for the table of where the organic carbon sample locations are, see Appendix J – Organic carbon lab results). These sites were mostly found around the perimeter of the bogs and the change in sites from peat to non-peat across bogs ranged between 4–54%. The largest changes were from around the perimeter of Ohinewai (54%), Ohote (47%), Kopuatai (45%), Hauraki (37%). These measured non-peat sites were excluded from Figure 10.

Mean thicknesses for measured peat (>0.3 m thick) spanned from 2.2 (Komakorau) to over 8 m (Te Mimiha), while median values showed a similarly broad range, from 1.2 m in Lower Waikato to 7.6 m at Te Mimiha. Median values for intermediate thickness bogs such as Moanatuatua (3.3 m), Orini (4.6 m), Rukuhia (6.7 m), and Hoe O Tainui (6 m) demonstrate substantial peat thickness across large areas. The interquartile ranges show substantial variability in peat thickness across the bogs, with some bogs (e.g., Rukuhia, Orini, Ohinewai, and Te Mimiha) having consistently deep peat where even the lower quartile exceeds ~3 m, while others (e.g., Kainui and Ohote) are dominated by shallow peat with lower quartiles near 0.3 m (non-peat) and upper quartiles below 3 m. Sample sizes varied considerably, with Hauraki East, Ohote, Ohinewai and Te Mimiha largely underrepresented with 10 or less peat sites per bog, while Komakorau, Moanatuatua, and Huntly were well represented with to over 200 sites. This influences the confidence and resolution of contour and transect interpretations. For more detail, see the bog summary statistics in Table 10 in Appendix K – Summary statistics and other results.

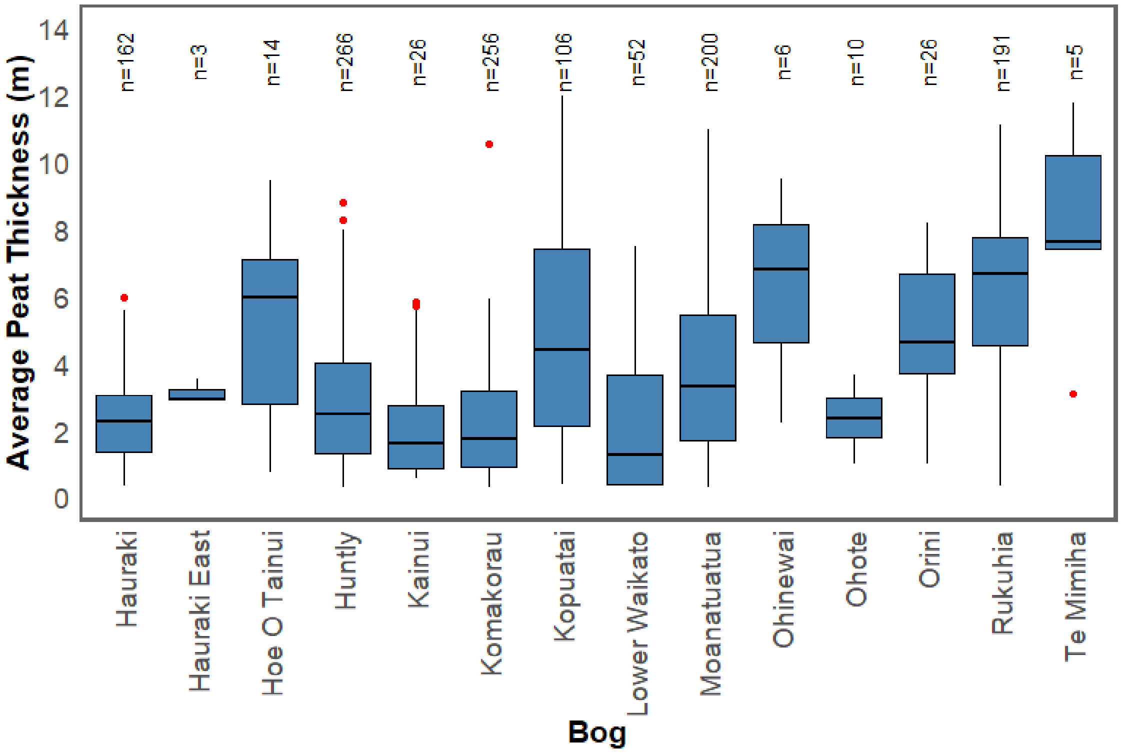


Figure 10. Boxplots showing the average and distribution of measured peat thickness (m) across 14 Waikato bogs. Peat thickness includes all measured points that are classified as peat (>0.3 m). Each box represents the interquartile range (Q1–Q3), with the horizontal line indicating the median thickness and whiskers extending to the minimum and maximum values. Red points denote outliers beyond this range. Sample sizes (n) for each bog are shown above the boxes. Note: 1) that Huntly measurements are depth to mineral subsurface, while Lower Waikato combines thickness and depth to mineral subsurface where peat thickness was not available and 2) some peatlands grouped in Table 2 are displayed individually here e.g., Hauraki, Hauraki East, & Kopuatai.

Contour maps produced using the methods described in section 2.5 provide a visual overview of peat distribution and thickness across the mapped peatland surface area. Each map displays the location of peat thickness measurement sites alongside labelled, colour-coded contour lines interpolating thickness across the entire bog area. The Organic Soils boundary shown in these maps follows the definition outlined in section 2.5.4. Hashed areas indicate zones where peat is less than 1 m (but greater than 0.3 m) thick; these areas should be treated with caution due to uncertainty in boundary confidence. The contour maps show that peat thickness patterns across the Waikato peatlands are broadly consistent across bogs despite differences in size, geomorphology, and degree of modification. Most bogs display a characteristic thick–to–thin gradient from centralised interior domes within basins toward thinner mineral boundaries/margins. This produces concentric or elongate contour patterns with some localised irregularities (e.g., abrupt thinning, mineral ridges/hills) that reflect the developmental constraints and history of each bog. Variations primarily reflect differences in disturbance levels (e.g., drainage history, excavation), sampling density, or underlying basin shape and geomorphology.

Profile (cross-sectional) transects complement the contour maps by illustrating peat thickness as the difference between surface elevation and elevation at the base of the peat, as described in section 2.5.3. These profiles provide insight into above- and below-ground topography, highlighting features such as doming, depressions, thinning of peat near margins, and abrupt transitions where peat meets mineral soils. In most cases, surface and base elevations follow parallel topographies, showing dome shaped accumulations with progressive edge thinning.

Together, the contour maps and profiles provide both horizontal and vertical perspective for interpreting peatland morphology in the region.

It is important to note that peat thickness (measured) values in Figure 10 differ from those (modelled values) displayed in contour maps and transect profiles (Figure 11 to Figure 39). The model generally underestimates peat thickness, with mean and median thickness, ~58% and ~74% lower on average than measured peat thickness, respectively. In contrast, modelled maximum peat thicknesses were only 19% lower on average than measured maxima, suggesting the model captures the broad range of peat thicknesses but tends to predict a much larger portion of shallow peat. This is more likely attributable to the exclusion of non-peat (<0.3 m) measurements from the measured statistics. Whereas, the modelled statistics derive results from all measured sites, including sites with thickness <0.3 m, which are an important part of the prediction of the contours, so cannot be excluded. However, this causes a skew in the data towards shallow peat. For example, in some cases, up to 54% of sites re-surveyed in 2023 were non-peat. Across all peatlands, Kopuatai seems to show the closest agreement between measured and modelled statistics, with the smallest mean bias (approximately 30% lower than measured) and near-identical maximum peat thickness values. In the following sections, where measured profiles indicate thicker peat, sometimes both measured and modelled values are reported, and the predictive limits of the contour model are acknowledged. Tables of the measured versus modelled peat thickness statistics are available in Appendix K – Summary statistics and other results.

3.1.1 Hauraki

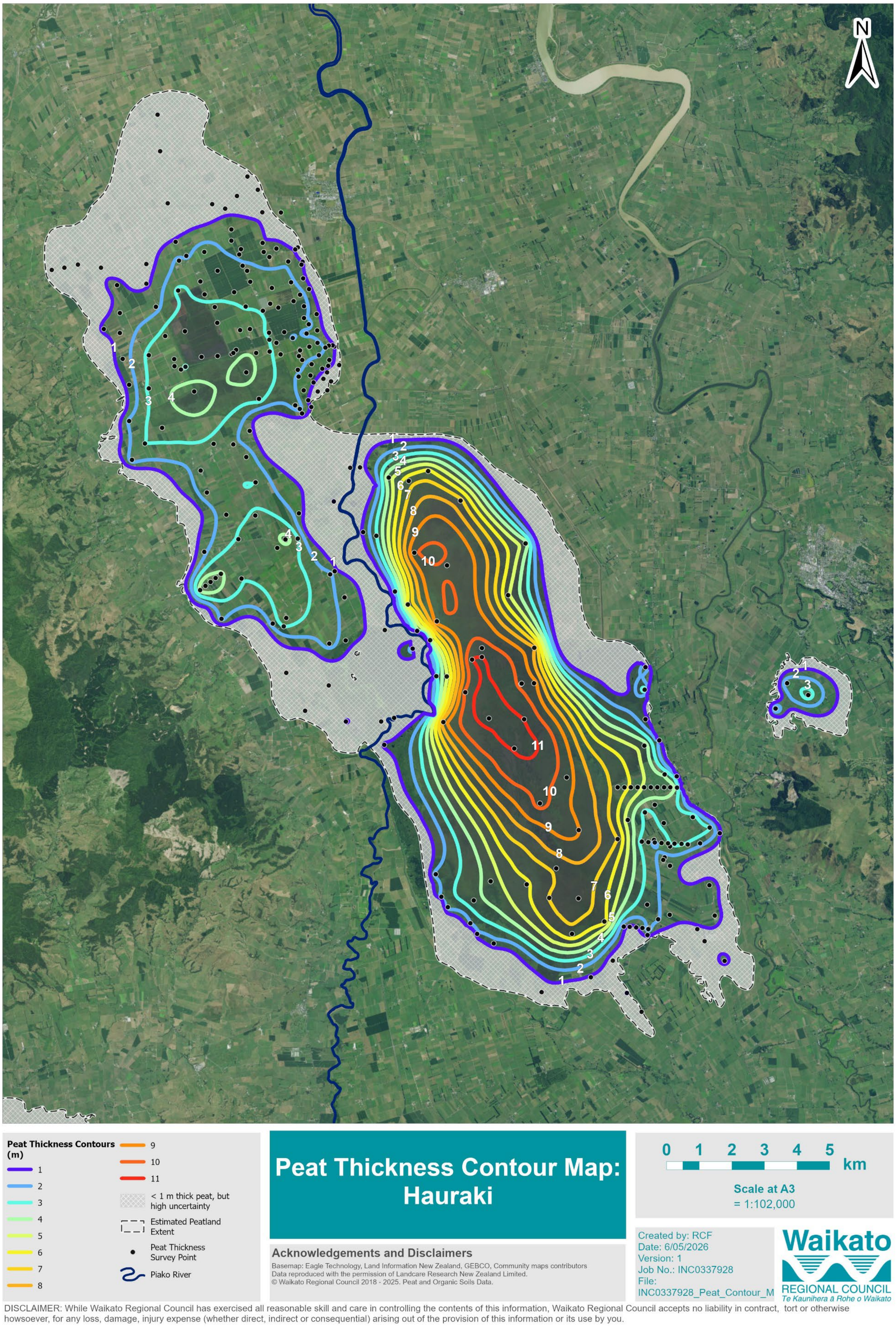


Figure 11. Map of Hauraki showing interpolated peat thickness (metres) represented by coloured contour lines for upper northern Torehape/Pouarua and southern Kopuatai (mostly intact), separated by the Piako River (navy blue line). Hauraki East is located to the east of Kopuatai.

There are three peatlands on the Hauraki plains (Figure 11): the main Torehape/Pouarua basin, Kopuatai basin, and Hauraki East. Torehape is geographically separated from Kopuatai by the Piako River, while Hauraki East is a small, spatially independent peatland approximately 3 km east of Kopuatai, separated by mineral soils. Kopuatai contains peat exceeding 11 m thick, while contours show a steep gradient from the centre outward, showing clear doming. Torehape shows peat deposits up to 4–5 m, while peat thickness in Hauraki East does not exceed 4 m.

Across Torehape, the NW–SE transect spans approximately 23 km (Figure 12 & Figure 13), with surface elevation ranging from ~0 m to 6.5 m above sea level (m asl). Base elevation dips as low as -2 m asl in several central sections, creating peat thicknesses of ~4 m. The profile shows a relatively flat surface with localised rises near 10–14 km, corresponding to mineral soil margins. The SW–NE transect (spanning ~12 km) exhibits slightly greater variability in surface elevation (up to 10 m asl), while base elevation reaches -1.6 m asl. The contour model predicts that peat thickness does not exceed 5 m, however the maximum value recorded in the field data is 5.95 m. As noted in section 3.1, model predictions were systematically lower than measured peat thicknesses for all bogs.

In the Kopuatai basin, both transects reveal extensive peat deposits. The W–E transect (~12 km in length) shows the average surface elevation is ~4 m, while base elevation drops to -6 m asl in the centre, producing peat thicknesses of up to 10 m (Figure 14). A sharp rise in surface elevation at the eastern end (to ~13 m asl) reflects the transition to mineral soils. The NW–SE transect (~20 km in length) displays similar patterns, with base elevation reaching -7.2 m asl and surface elevation remaining relatively flat (~1–5 m asl), confirming the presence of one of the deepest peat deposits in the region.

There were few sites visited across Hauraki East. Therefore, transects were not presented across this bog. Hauraki East was not measured as part of the original Davoren (1978) survey, and the five observation sites available were collected opportunistically towards the end of the 2023 survey. As a result, the interpolated contours for this bog are weakly constrained and should be interpreted as indicative only, reflecting low confidence in the modelled spatial representation. Additional measurements would be required to confidently characterise peat thickness patterns in this area.

Across Hauraki, peat thickness is greatest in the centre of the domes with thicknesses exceeding 10 m in Kopuatai and 5 m in Hauraki. Peripheral zones exhibit thinner peat (<1 m) and more variable surface elevation, reflecting transitions to mineral soils and drainage margins. Base elevation (and at times surface elevation) are below sea level.

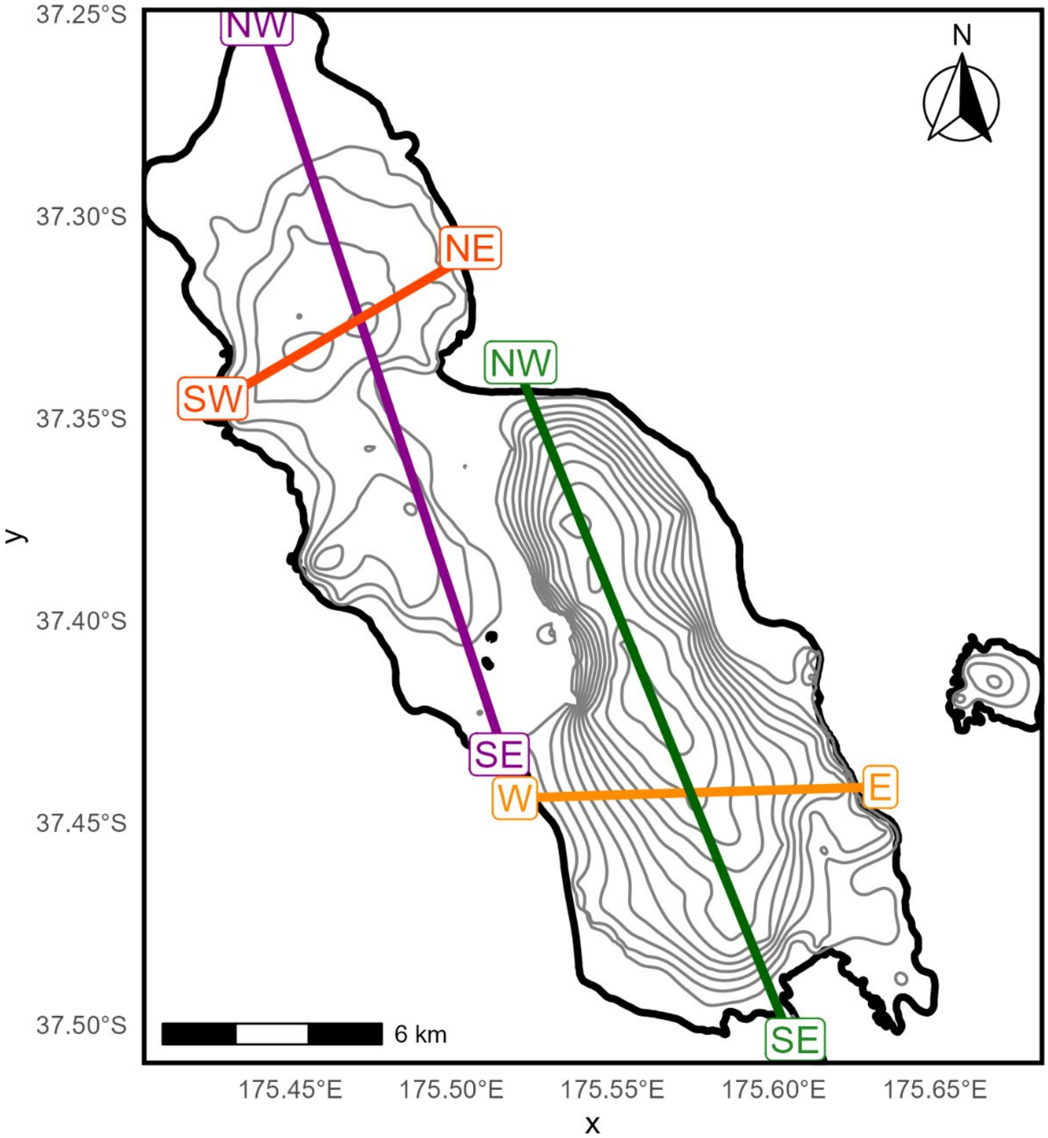


Figure 12. Hauraki peatland complex showing the Torehape/Kopuatai peatland boundaries with peat thickness contour lines and the positions of the transects in Hauraki: northwest–southeast (purple) and southwest–northeast (orange); and Kopuatai: northwest–southeast (green) and west–east (light orange).

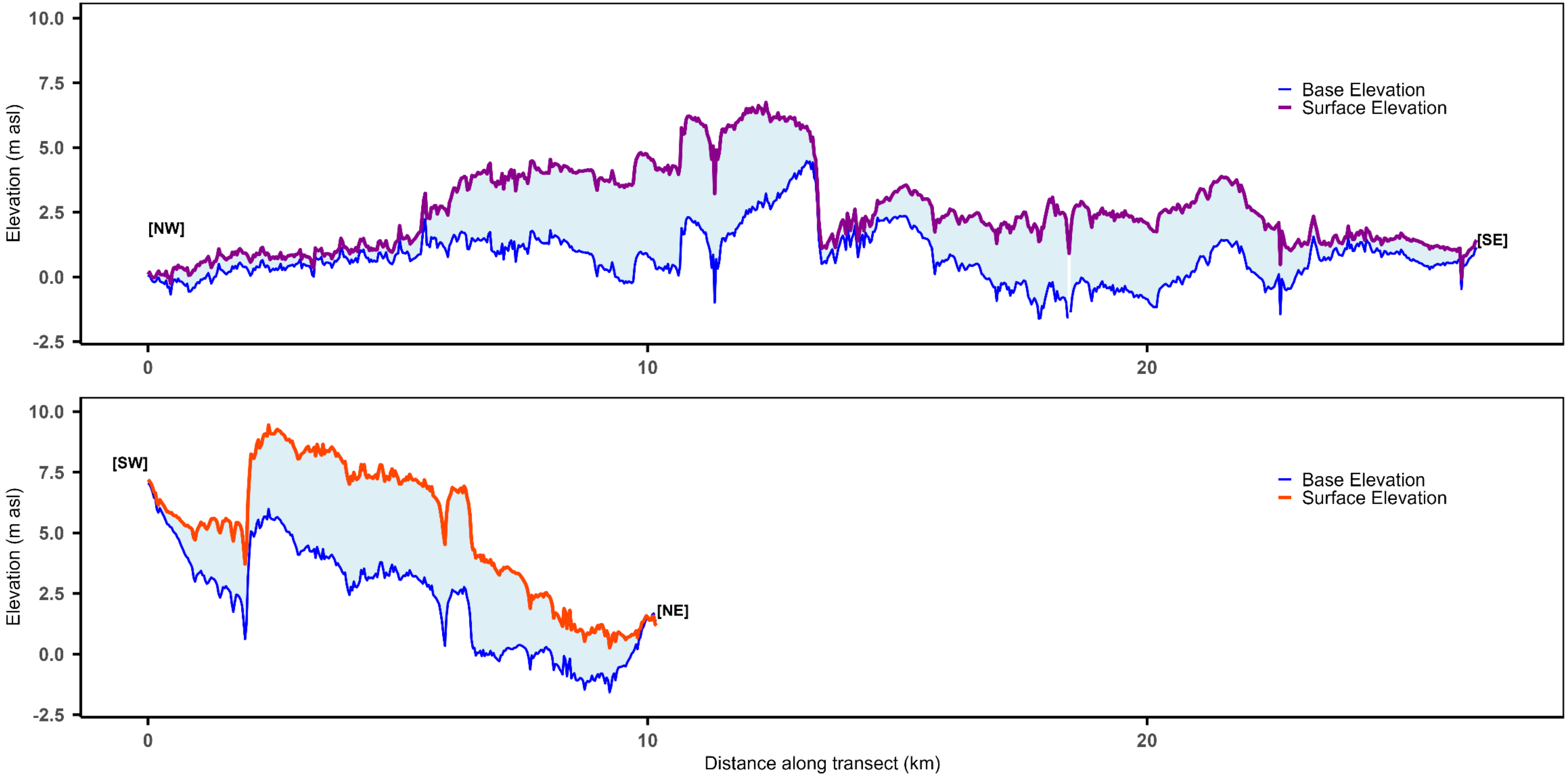


Figure 13. Elevation profiles plotted against distance of two transects across Torehape (location shown in Figure 12), with surface elevation (purple for northwest–southeast, orange for southwest–northeast) and peat base elevation (blue).

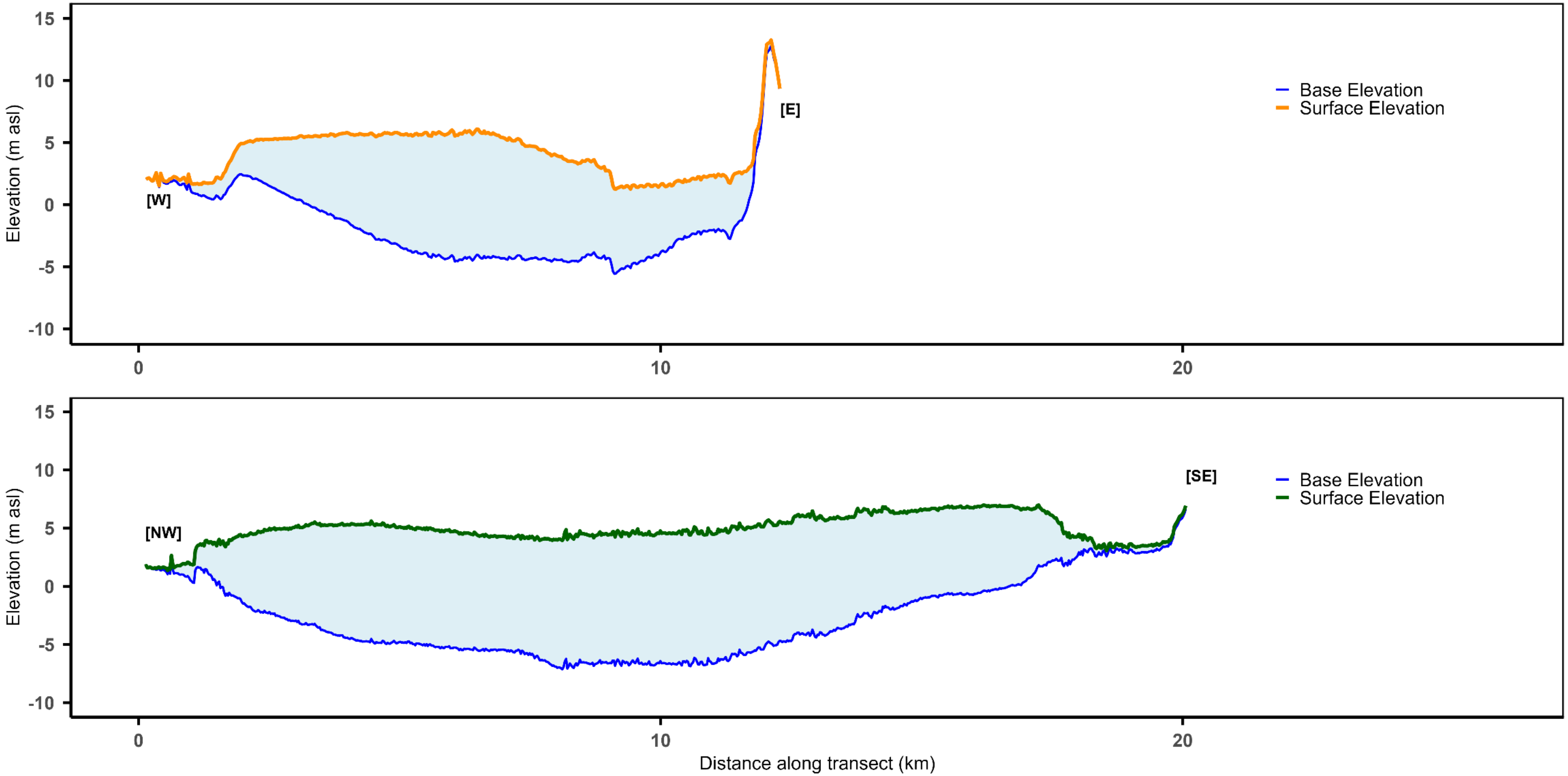


Figure 14. Elevation profiles plotted against distance of two transects across Kopuatai (location shown in Figure 12), with surface elevation (light orange for west–east, green for northwest–southeast) and peat base elevation (blue).

3.1.2 Hoe o Tainui

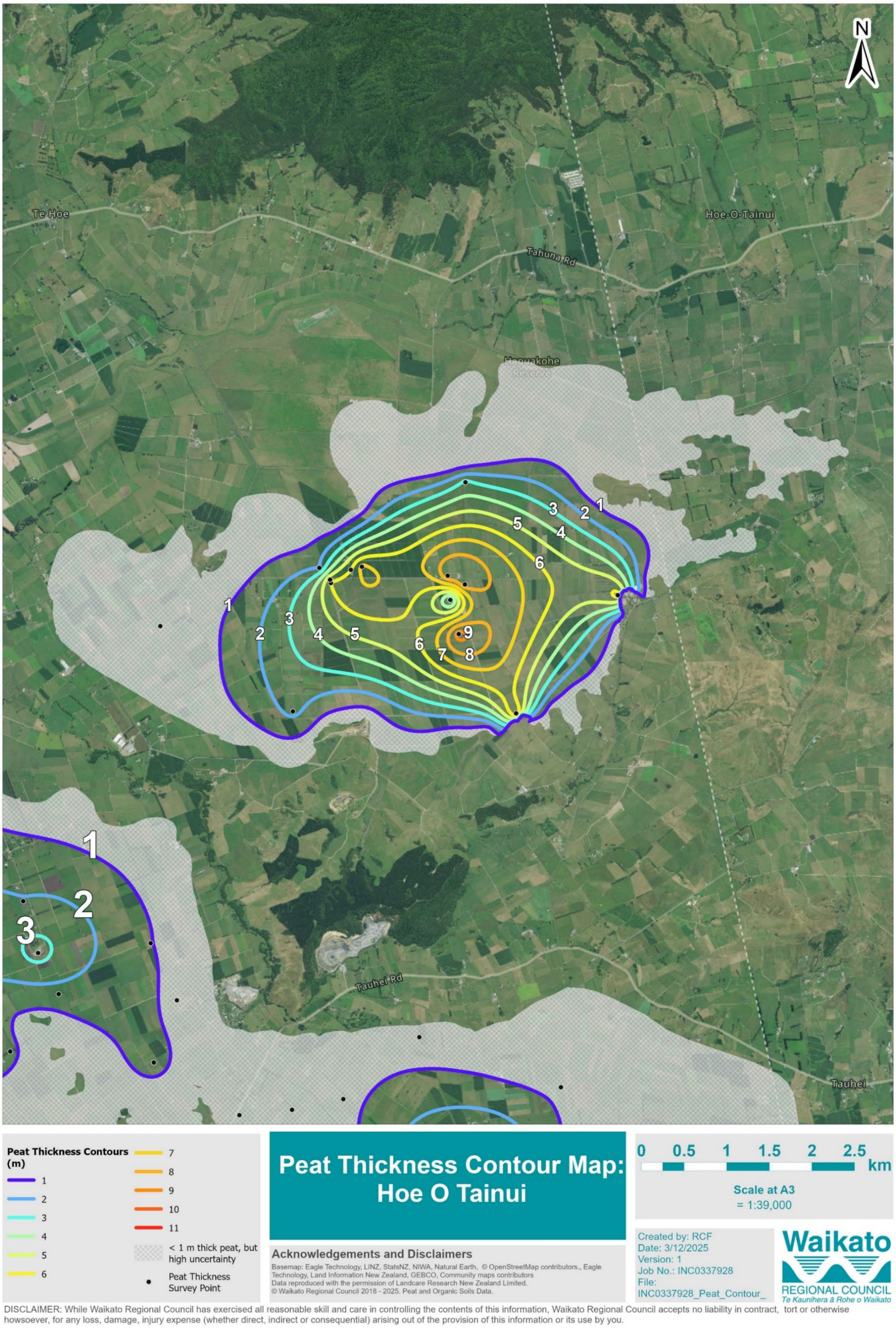


Figure 15. Map of Hoe o Tainui showing interpolated peat thickness (metres) represented by coloured contour lines.

The Hoe o Tainui peatland covers an area of approximately 1,900–2,300 hectares, forming a compact basin with a central dome exceeding 9 m thickness in the centre. The W–E transect spans approximately 10 km across the peatland. Surface elevation ranges from ~18 m to 26 m above sea level (m asl), revealing a pronounced dome structure. Base elevation also varies dramatically, dipping to ~12 m asl in the central section and rising to ~20 m asl near the ends. This creates a broad depression beneath the surface, resulting in a range of peat thicknesses, with the thickest deposits occurring between 4–7 km along the transect where base elevation is lowest. While the dome shape is still evident when looking across the N–S transect (~4.5 km in length), there is also a gradual rise toward the eastern margin. Surface elevation remains relatively high (20–25 m asl), while base elevation drops steeply to ~12 m asl in the centre, producing peat thicknesses exceeding 9 m in the deepest section. The northern end shows a slight depression in surface elevation, while the southern end rises sharply, suggesting a sloping margin toward mineral soils. This profile indicates a well-developed peat dome with significant peat accumulation. Both transects confirm that Hoe o Tainui contains deep peat deposits, particularly along the N–S axis.

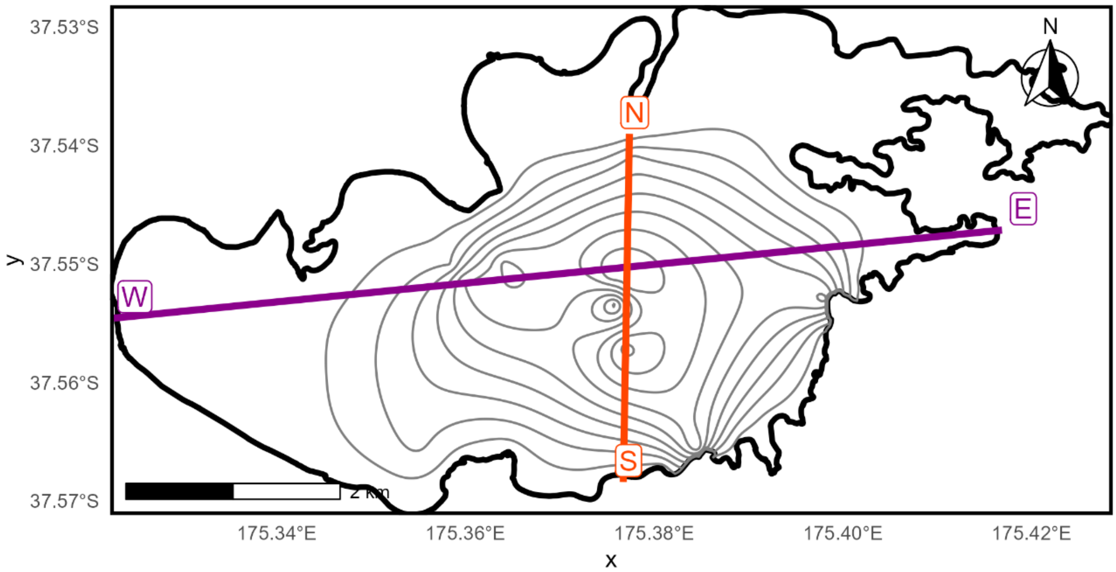


Figure 16. Hoe o Tainui peatland showing the peatland boundary with thickness contour lines and the positions of the transects: west–east (purple) and north–south (orange).

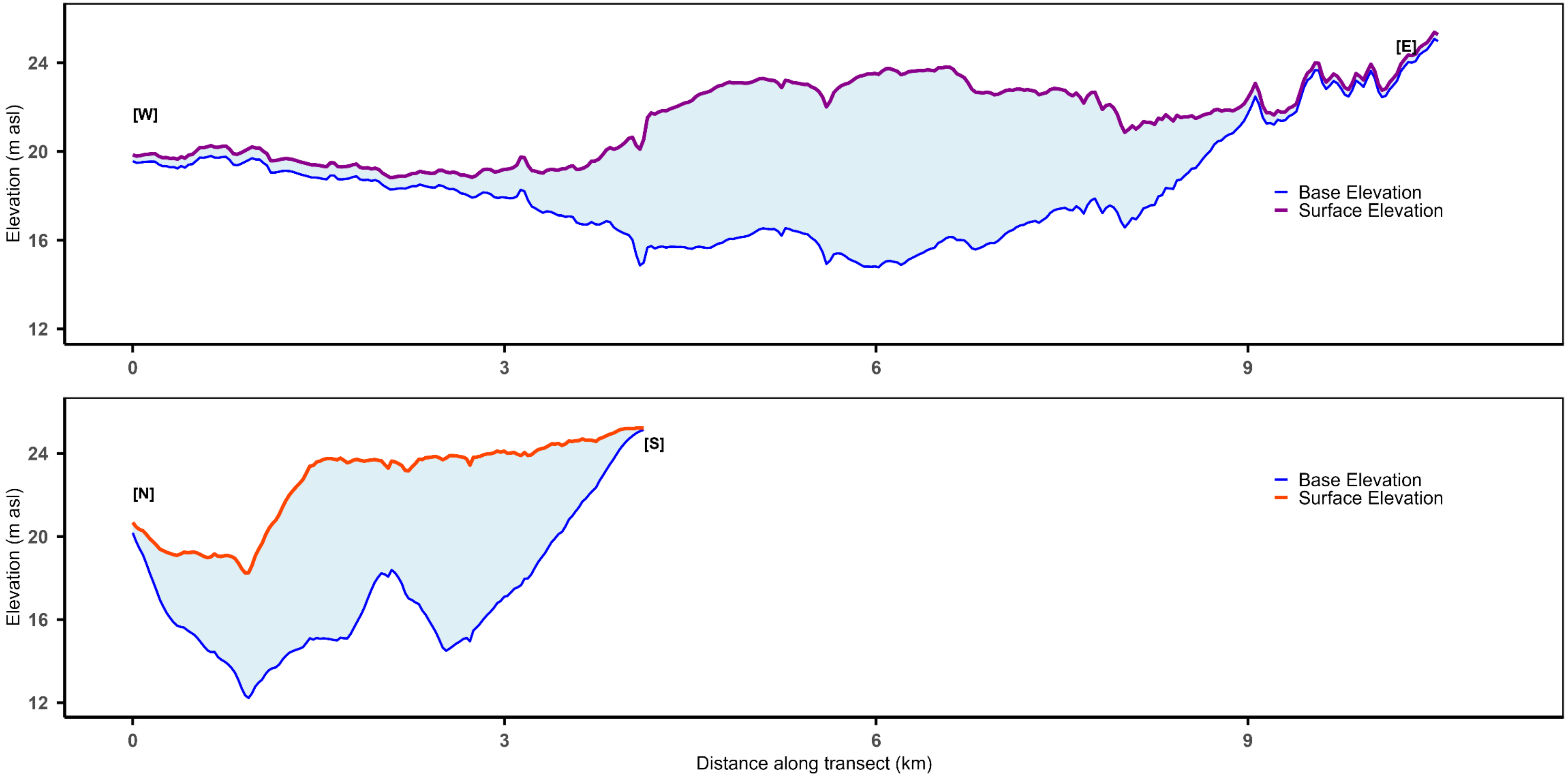


Figure 17. Elevation profiles plotted against distance of two transects across Hoe o Tainui (location shown in Figure 16), with surface elevation (purple for west–east, orange for north–south) and peat base elevation (blue).

3.1.3 Huntly

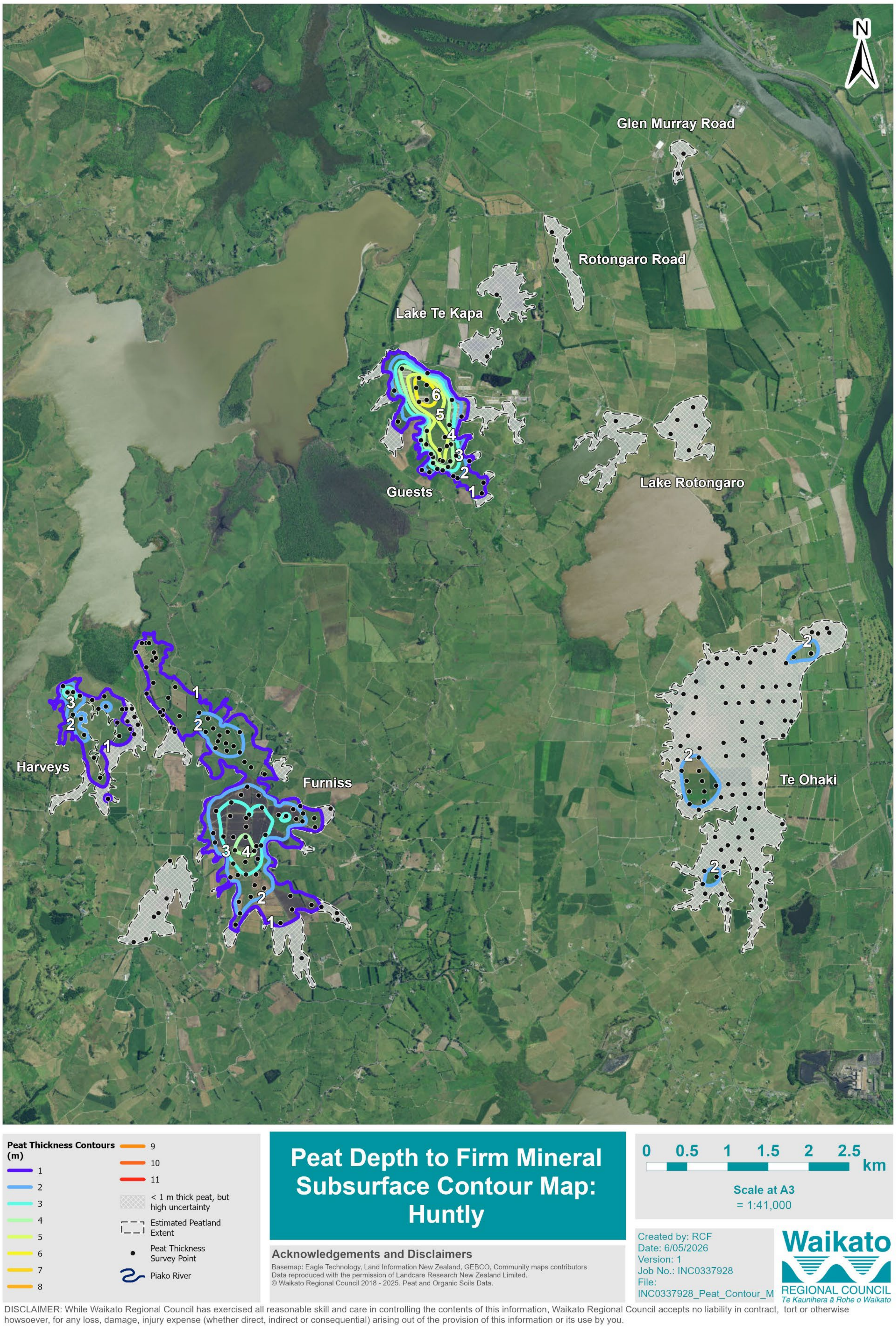


Figure 18. Map of Huntly showing interpolated depth to firm mineral material (metres) represented by coloured contour lines. Values represent depth to firm mineral substrate and are not directly equivalent to peat thickness.

The Huntly peatland complex (naturally disconnected system) comprises multiple small peat deposits scattered across the landscape (Te Ohaki, Furniss, Guests, Harveys, Rotongaro Road, and Lake Rotongaro and Te Kapa bog units), collectively covering over 1,000–3,000 hectares. These deposits are disconnected, narrow basins with localised peat domes. The deepest peat occurs within Guests and Furniss bogs, where depth to firm mineral material exceeds 6 m, while deposits in other bogs generally range between 2–3 m. The large range in depth could be explained by use of *depth to firm mineral subsurface* in the Huntly dataset as opposed to thickness, so it is unclear where the boundary of peat to soft mineral substratum is (thickness). Note also that the model had difficulties in these areas and did not produce contours for some bogs (e.g., Lake Rotongaro) and did not produce a 1 m contour line for Te Ohaki bog, so the range of uncertainty indicated by the hashed area in Figure 18 is between 0.3–2 m, rather than 0.3–1 m as indicated in the other bogs.

Transects produced for Huntly show depth to firm mineral subsurface which isn't comparable to other bogs and isn't an accurate side profile of peat and it is unclear where the peat and soft, fluid silt layers are located throughout the profile. Additionally, there were few sites for smaller bogs such as Lake Rotongaro. Therefore, transects are not presented for Huntly.

3.1.4 Kainui

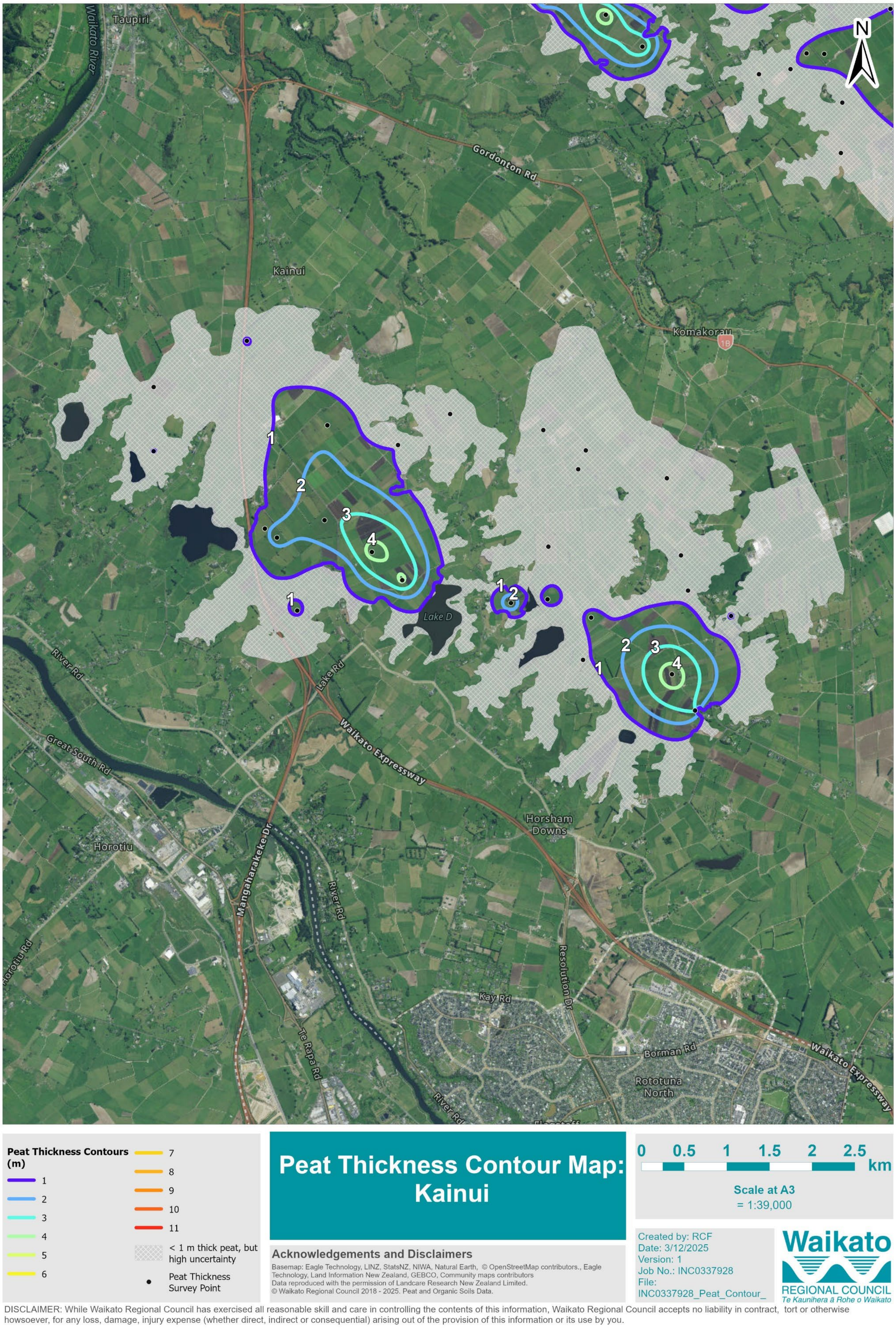


Figure 19. Map of Kainui showing interpolated peat thickness (metres) represented by coloured contour lines.

Kainui peatland is relatively small, covering approximately 2,300–3,000 ha, and is characterised by multiple peat domes separated by mineral soil ridges/hills. Kainui consists of multiple small peat deposits (bogs), with the deepest peat reaching 4–5 m, while most areas are shallow (<2 m).

The transect spans ~10 km across the bog, intersecting two peat domes. Surface elevation ranges from ~18 m to 36 m above sea level (m asl), with sharp rises at approximately 2 km and 6 km along the transect, corresponding to hills or mineral soil ridges. Base elevation varies between ~17 m and 21 m asl. Peat thickness is greatest between 3–6 km, where base elevation is lowest (~21 m asl) and surface elevation remains elevated (~25–28 m asl), producing thicknesses up to 4 m (measured thickness is up to 6 m).

Kainui has an irregular peatland morphology, with peat concentrated in localised depressions/domes dissected by mineral ridges/hills, rather than forming a continuous basin. The peripheral section near the NW end of the transect between 0–2 km, shows minimal peat accumulation (<1 m), likely due to positioning in between two ridges. This overall pattern suggests limited hydrological connectivity and a history of peat formation constrained by topography.

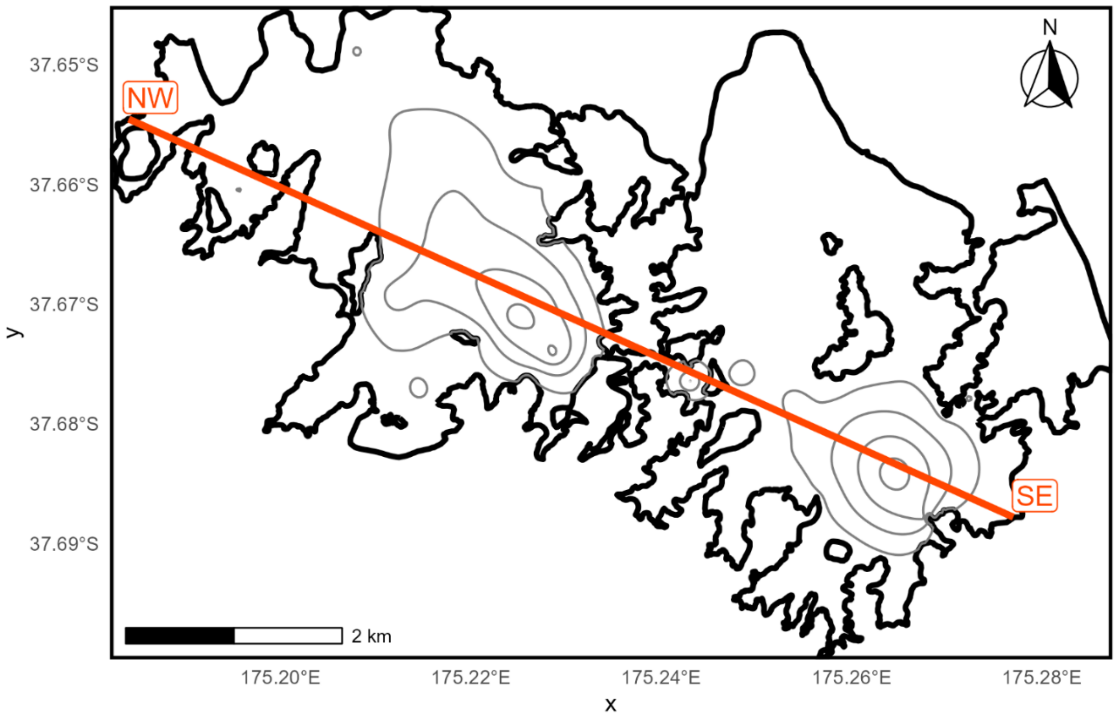


Figure 20. Kainui peatland showing the peatland boundary with contour lines and the position of the northwest–southeast transect (orange).

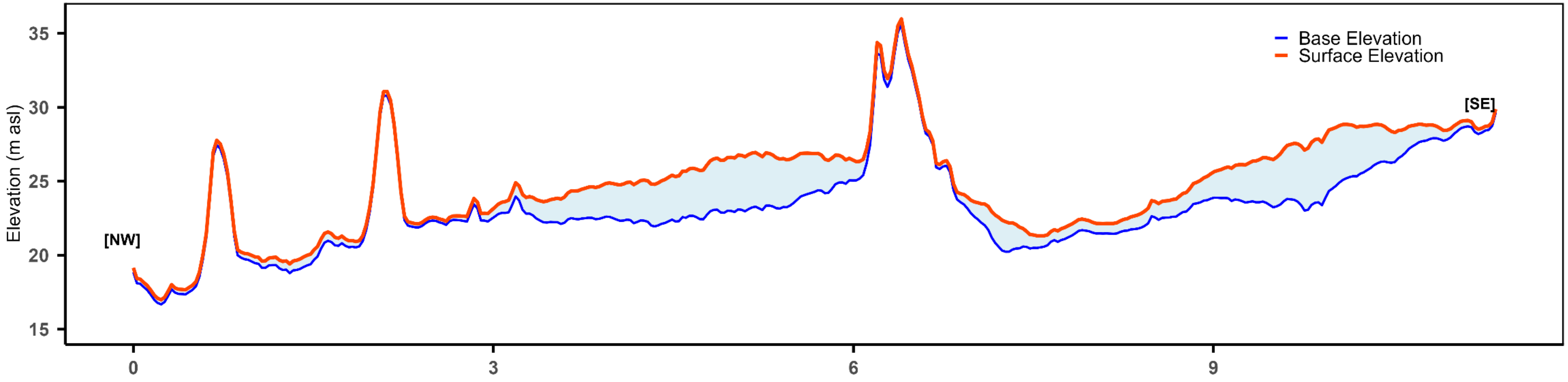


Figure 21. Elevation profile plotted against distance of northwest–southeast transect across Kainui (location shown in Figure 20), with surface elevation (orange) and peat base elevation (blue).

3.1.5 Komakorau

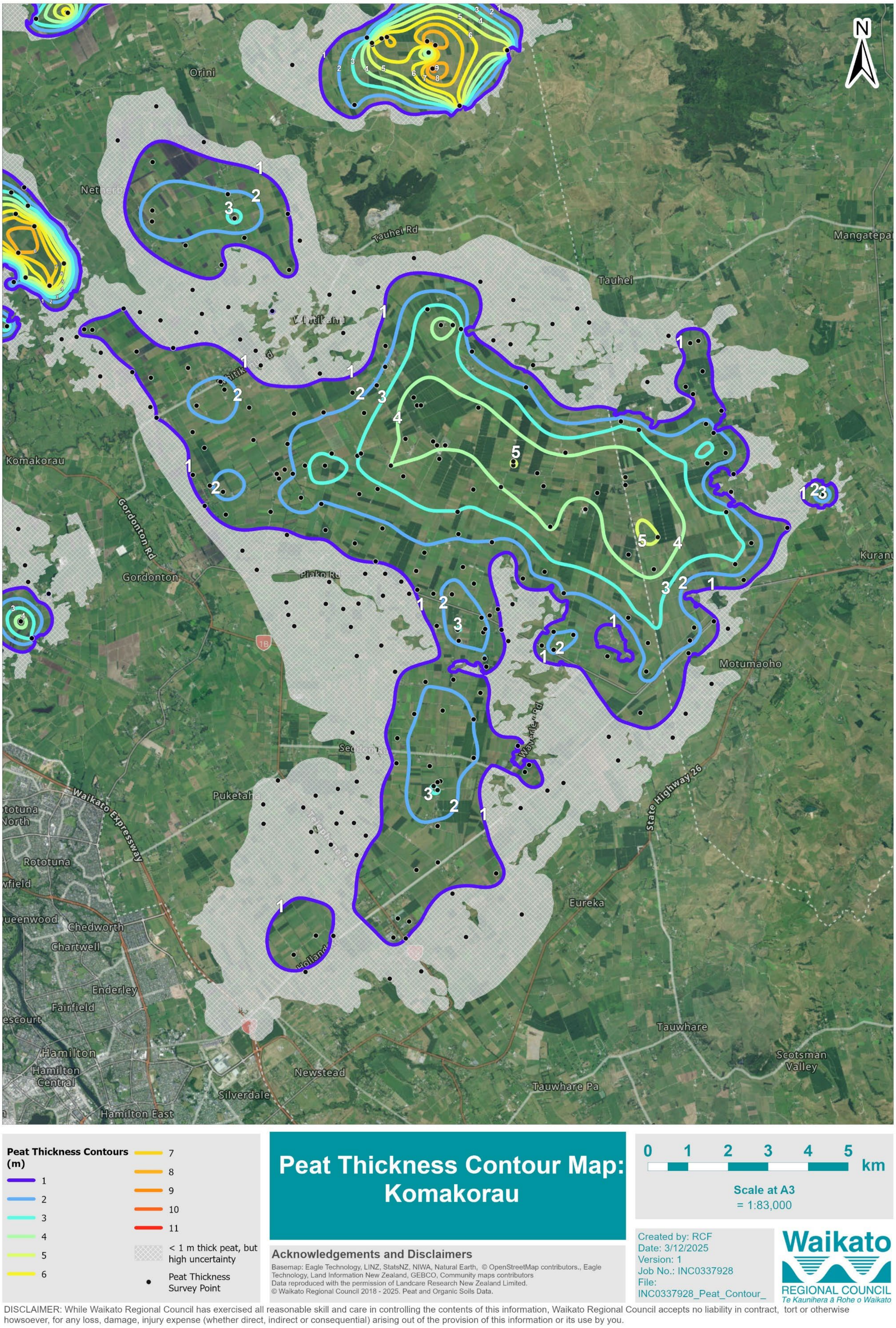


Figure 22. Map of Komakorau showing interpolated peat thickness (metres) represented by coloured contour lines.

Komakorau bog is the largest continuous peatland in the Waikato region, covering approximately 21,000–23,000 hectares. It consists of multiple peat domes within a broad basin with several areas of accumulation, intersected by some mineral soil ridges. The deepest peat reaches 5–6 m, while most of the basin contains peat between 2–4 m thick. So, whilst Komakorau is relatively large (226 km^2), it is shallow compared to other peatland, as reflected in its estimated volume (0.26 km^3). A single location to the NE measured peat as 10.5 m thick, but this is marked as an outlier in Figure 10.

The N–S transect spans ~25 km across the peatland. Surface elevation ranges from ~22 m to 42 m above sea level (m asl), with a steady rise toward the southern margin. Base elevation varies between ~22 m and 40 m asl, dipping in central sections to create peat thicknesses of 4–5 m. The northern end shows a depression in surface and base elevation (~22 m asl). Toward the south, surface elevation rises to ~44 m asl, but base elevation also rises, reducing peat thickness to <3 m near the boundary.

The NW–SE transect (~25 km in length) reveals a similar pattern, with surface elevation increasing from ~22 m to 36 m asl along the transect. Base elevation dips to ~28 m asl in the central section, producing peat thicknesses of 4–5 m between 12–20 km along the transect. Peripheral zones at both ends show thinner peat (<2 m), suggesting a gradual transition to mineral soils. The profile suggests a broad, gently sloping peat dome with localised depressions contributing to thicker deposits.

Komakorau exhibits extensive peat deposits concentrated in depressions (deeper in the northern end of the bog), with maximum thickness reaching 5 m along both transects. There appears to be large peripheral areas of thin peat (<2 m).

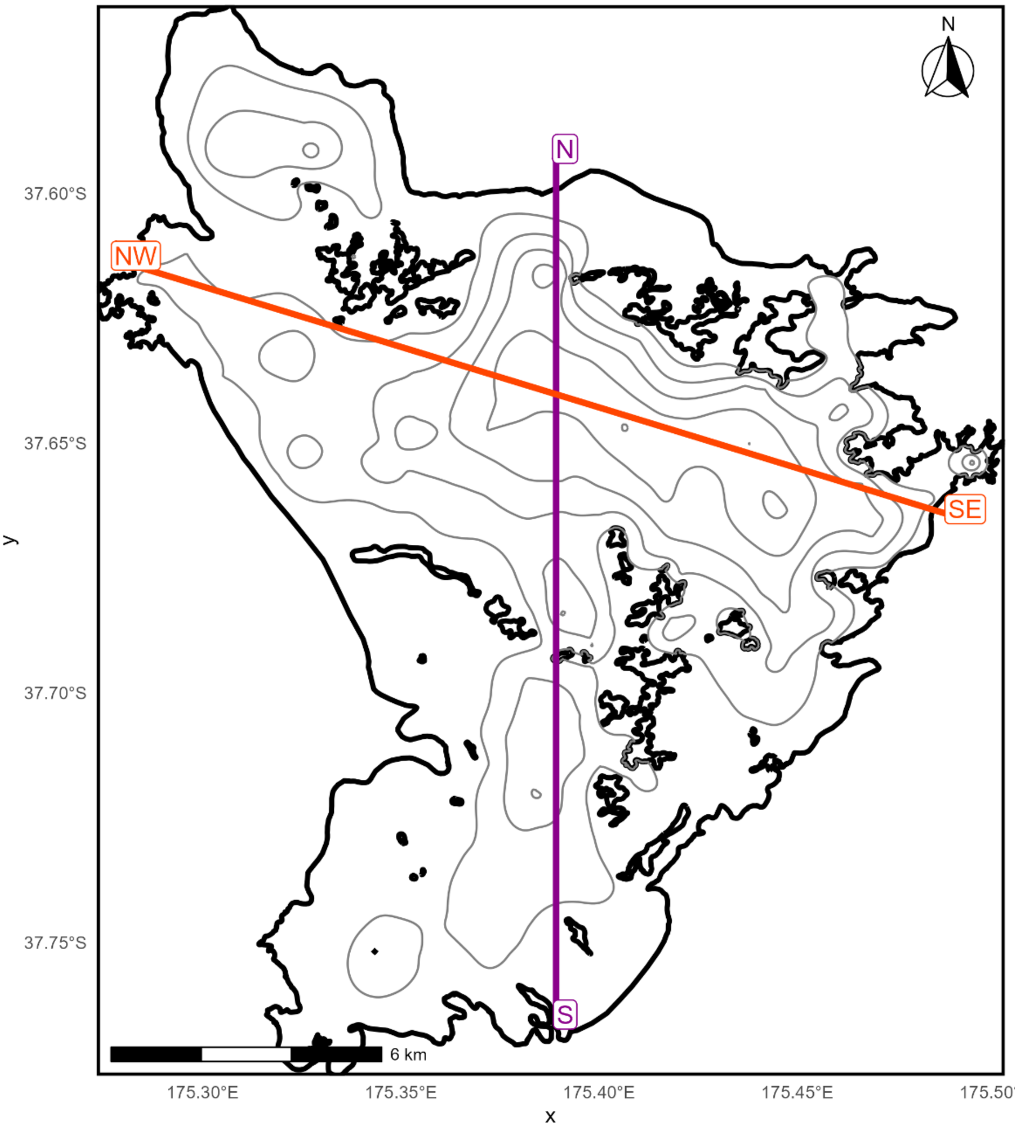


Figure 23. Komakorau peatland showing the peatland boundary with thickness contour lines and the positions of the transects: north–south (purple) and northwest–southeast (orange).

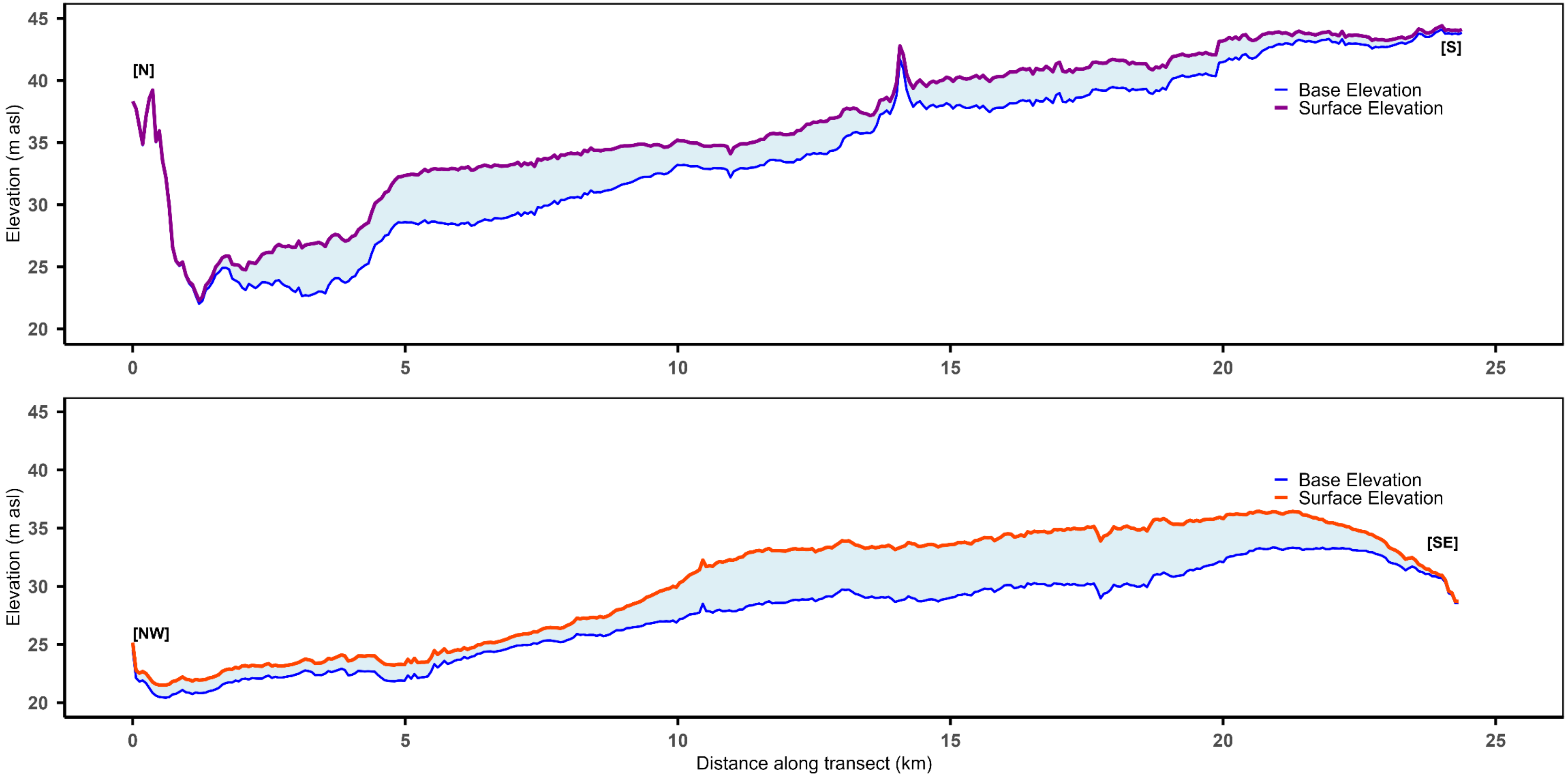


Figure 24. Elevation profiles plotted against distance of two transects across Komakorau (location shown in Figure 23), with surface elevation (purple for north–south, orange for northwest–southeast) and peat base elevation (blue).

3.1.6 Lower Waikato & Whangamarino

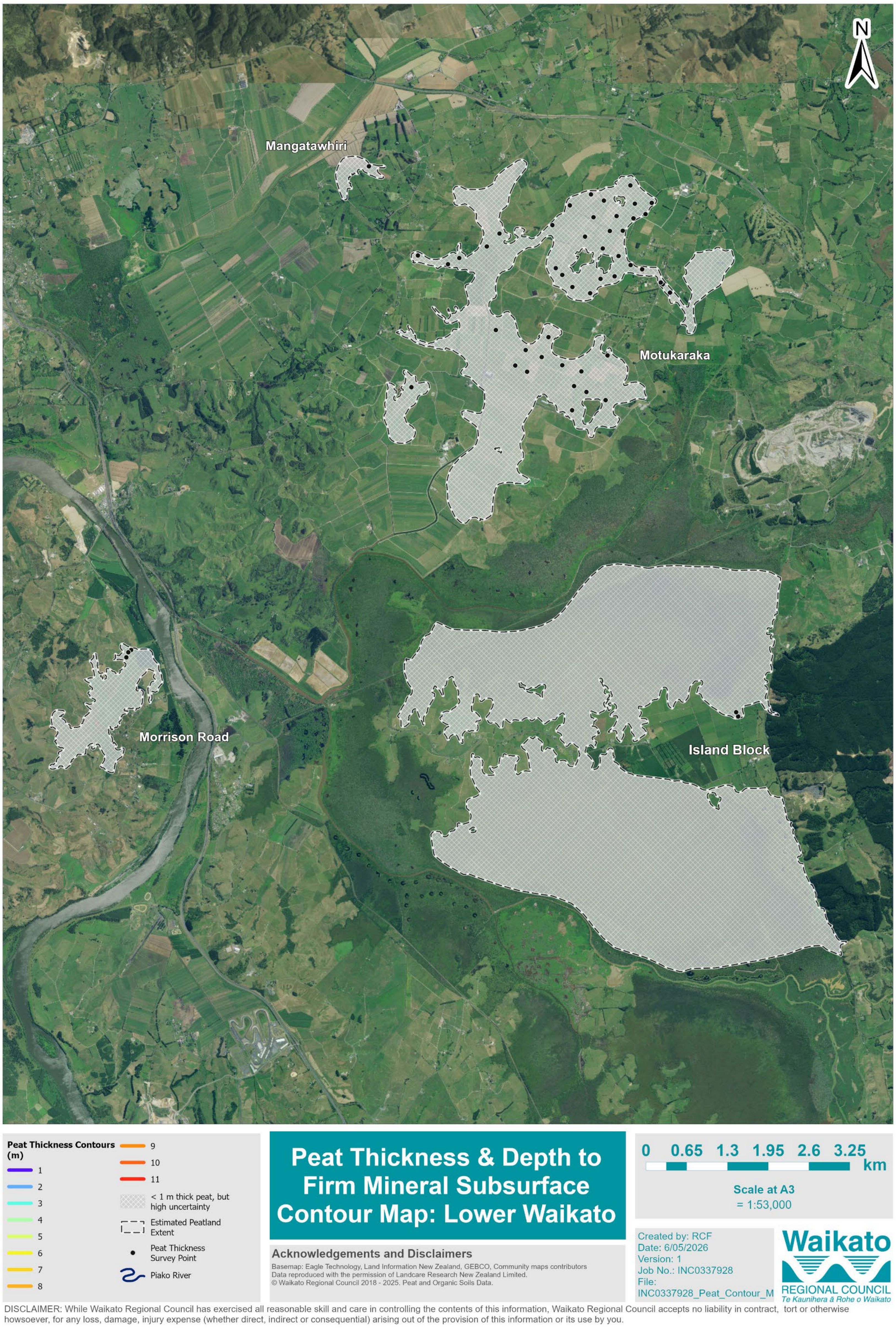


Figure 25. Map of Lower Waikato showing interpolated peat thickness and depth to mineral subsurface (metres) where thickness was unavailable, represented by coloured contour lines.

The Lower Waikato peatland complex, like Huntly, represents a group of smaller bogs (including Whangamarino/Island Block, Morisson Road, Motukaraka, and Mangatawhiri) separated by geographic structures (e.g., hills, streams, roads). No contours were created, indicating either shallow deposits or areas where peat thickness data is limited. The measured data shows peat thickness does not exceed 1 m for most of the peatland area in the Lower Waikato. Except for areas of Motukaraka, where peat thickness is up to 4.95 m and depth to mineral subsurface (with thickness data was unavailable) is up to 7.7 m at some sites, however, this is not shown in Figure 25 but is included in the box and whisker plot in Figure 10.

The large range in thickness could be explained using both *thickness* and *depth to firm mineral subsurface* values in the Lower Waikato dataset, so it is unclear where the boundary of peat to soft mineral substratum occurs (and thus, what the thickness is). For this reason, the transects produced for Lower Waikato are not presented and would not be comparable to other bogs. It also isn't an accurate profile of the peat, and it is unclear where the peat and soft, fluid silt layers are located throughout the entire profile. Additionally, there were few sites within all bogs.

3.1.7 Moanatuatua

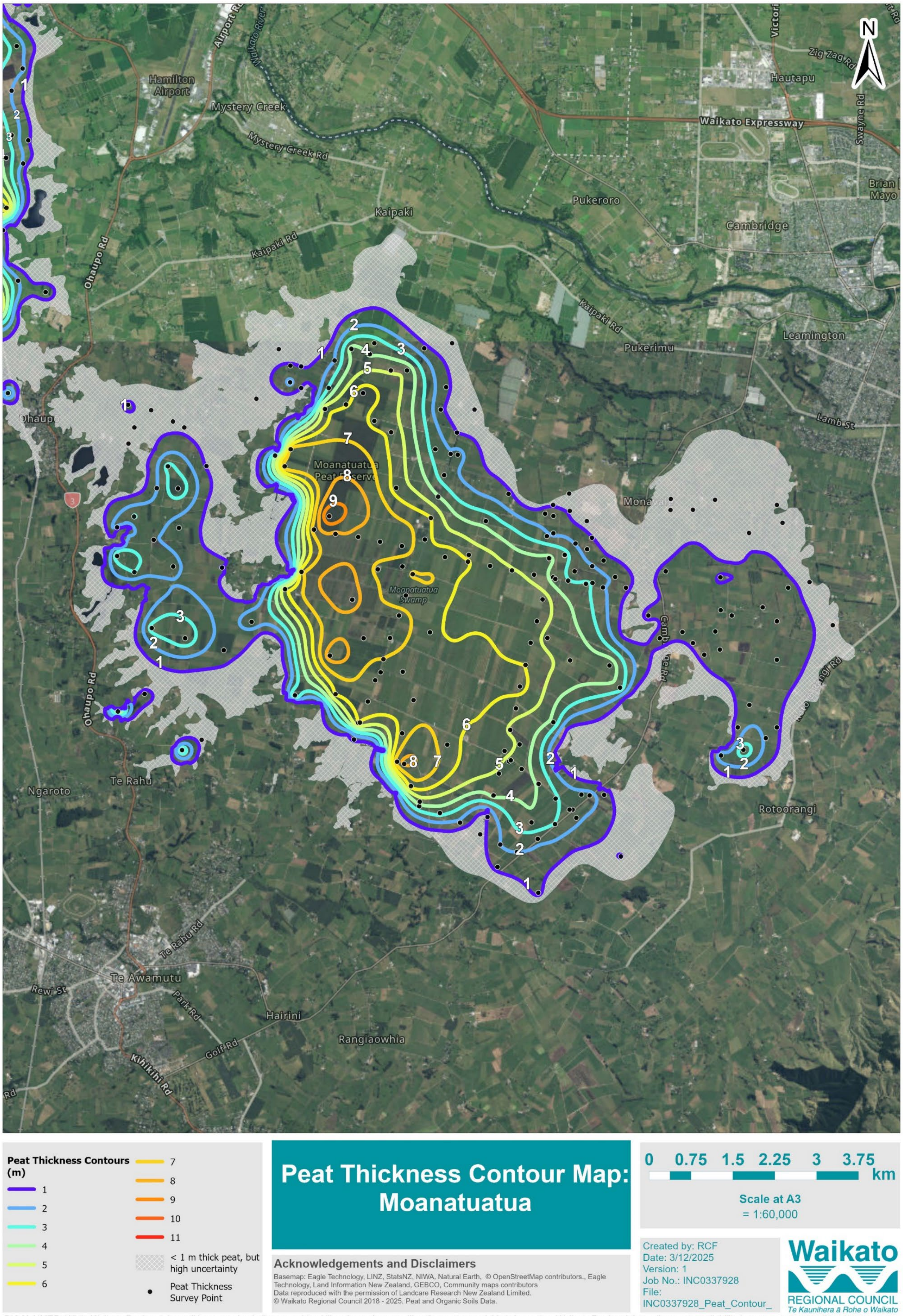


Figure 26. Map of Moanatuatua showing interpolated peat thickness (metres) represented by coloured contour lines.

Moanatuatua bog covers approximately 8,400–8,700 hectares. It is characterised by a central dome and extensive marginal zones, intersected by mineral soil ridges. The central area contains peat exceeding 9 m thick where the Moanatuatua Peat Reserve is located – the only remaining intact peat bog within the wider Moanatuatua peatland system. The contour pattern indicates a large, continuous peatland, with peat thickness surrounding the dome mostly ranging from 2–6 m.

The NE–SW transect spans ~18 km across the bog. Surface elevation ranges from ~50 m to 72 m above sea level (m asl), with sharp rises at ~2 km and ~5 km along the transect corresponding to mineral soil ridges. Base elevation varies between ~50 m and 65 m asl, dipping in central sections to create peat thicknesses of 6–9 m. The deepest peat occurs between 6–12 km along the transect, where surface elevation remains high (~65 m asl) and base elevation is low (~58–60 m asl). Peripheral zones at both ends show minimal peat accumulation (<2 m), reflecting transitions to mineral soils and disconnected terrain.

The SE–NW transect (~8 km) reveals a more uniform dome structure. Surface elevation ranges from ~56 m to 68 m asl, while base elevation dips to ~54 m asl in the centre, producing peat thicknesses of 6–8 m. The SE margin shows a steep rise in surface elevation (~68 m asl) but also a rise in base elevation, indicating a quick transition from peat <2 m thick, to a mineral ridge. This profile indicates a well-developed peat dome with significant peat accumulation in the central basin.

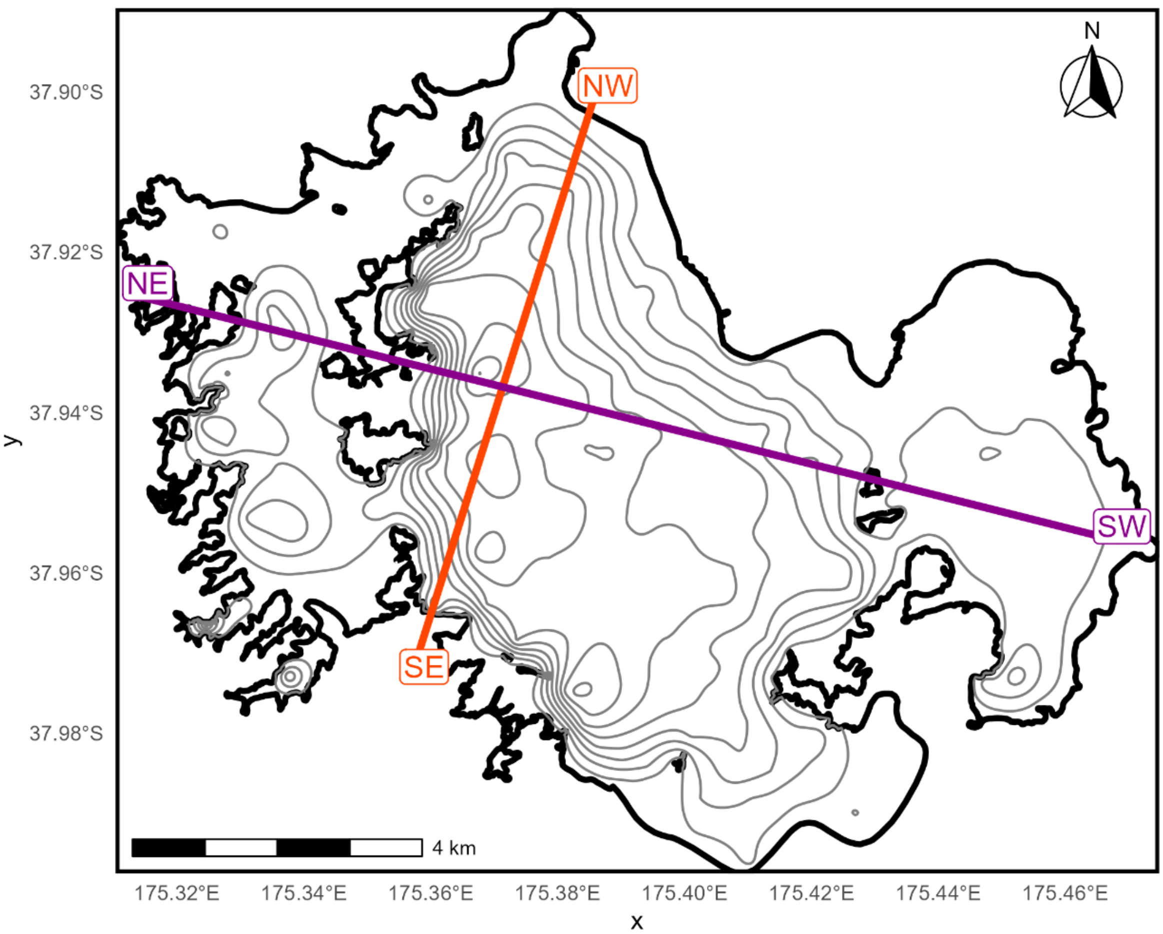


Figure 27. Moanatuatua peatland showing the peatland boundary with thickness contour lines and the positions of the transects: northeast–southwest (purple) and northwest–southeast (orange).

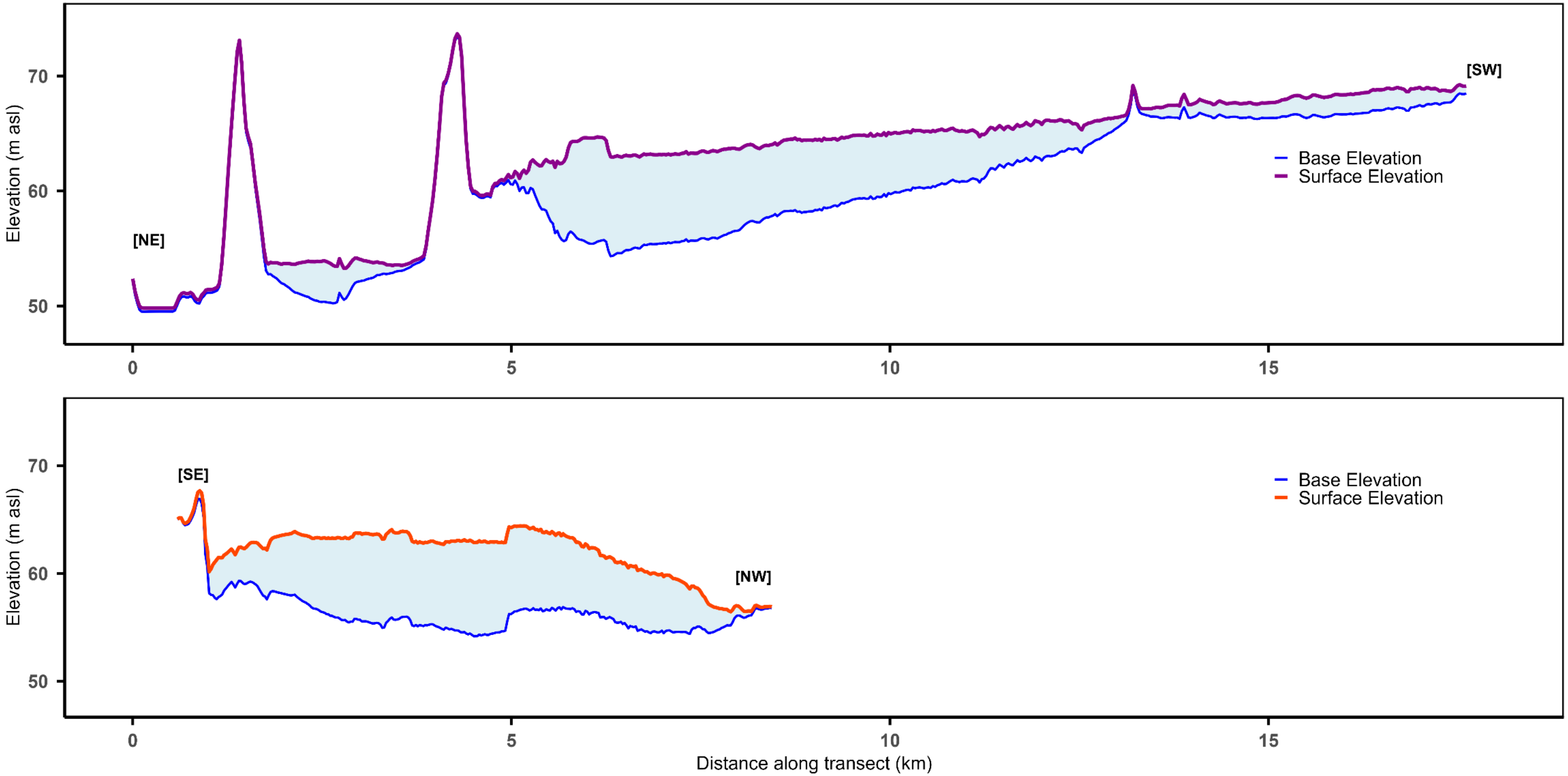


Figure 28. Elevation profiles plotted against distance of two transects across Moanatuatua (location shown in Figure 27), with surface elevation (purple for northeast–southwest, orange for southeast–northwest) and peat base elevation (blue).

3.1.8 Ohinewai

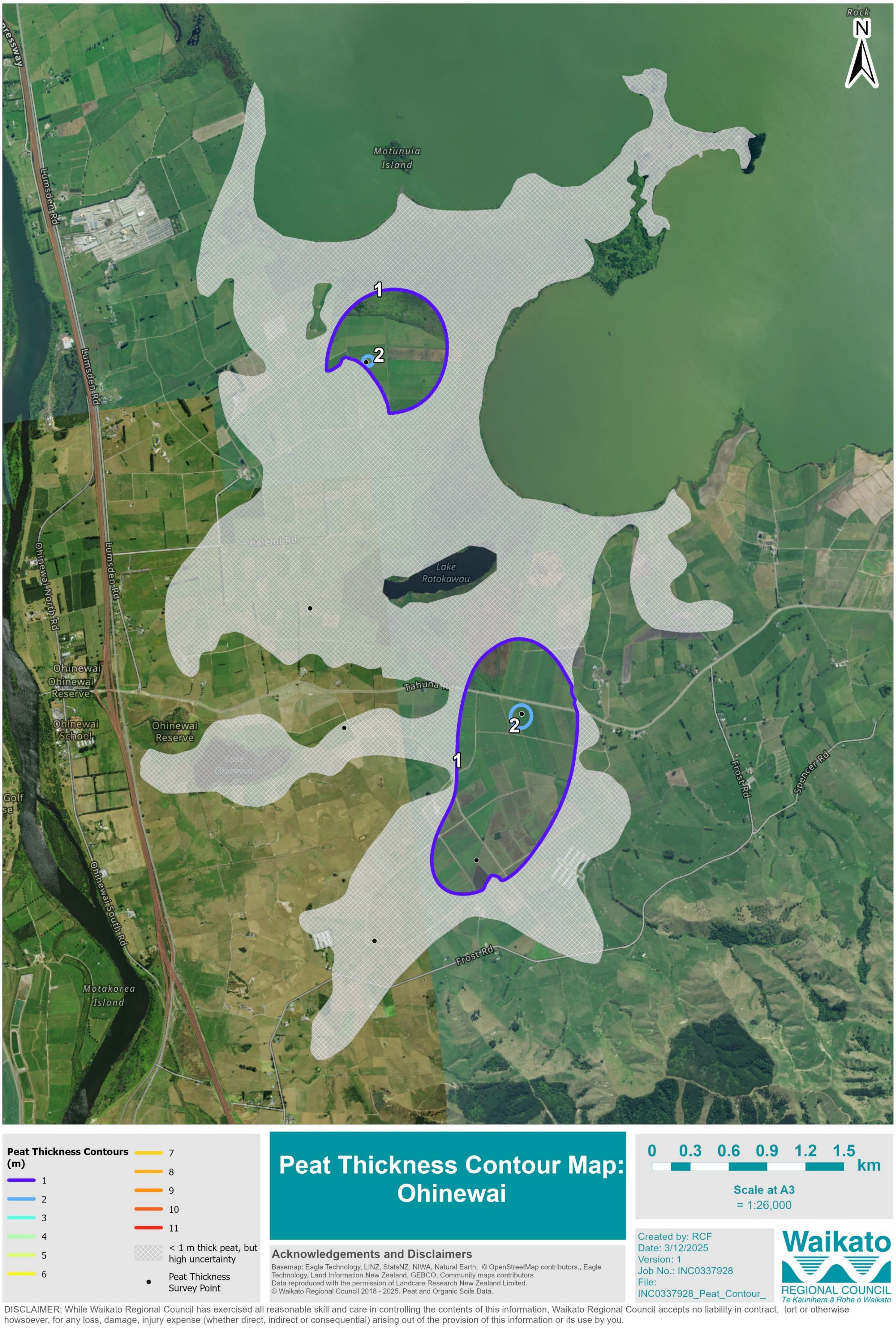


Figure 29. Map of Ohinewai showing interpolated peat thickness (metres) represented by coloured contour lines.

Ohinewai bog is a relatively small peatland, covering approximately 1,000–1,500 hectares. It is characterised by a narrow basin with disconnected shallow peat deposits. Ohinewai contains two main peat deposits and exhibits relatively shallow (<2 m) deposits compared to larger Waikato peatlands, with maximum thickness reaching ~3 m in central sections, although this observation is constrained by the limited number of measurements. Peripheral areas are dominated by thin peat (<1 m), indicating strong geomorphological control on peat formation. However, with few sites visited across this bog, it is difficult to draw any robust conclusions from the contours produced by the model. For this reason, transects were not presented across Ohinewai.

3.1.9 Ohote

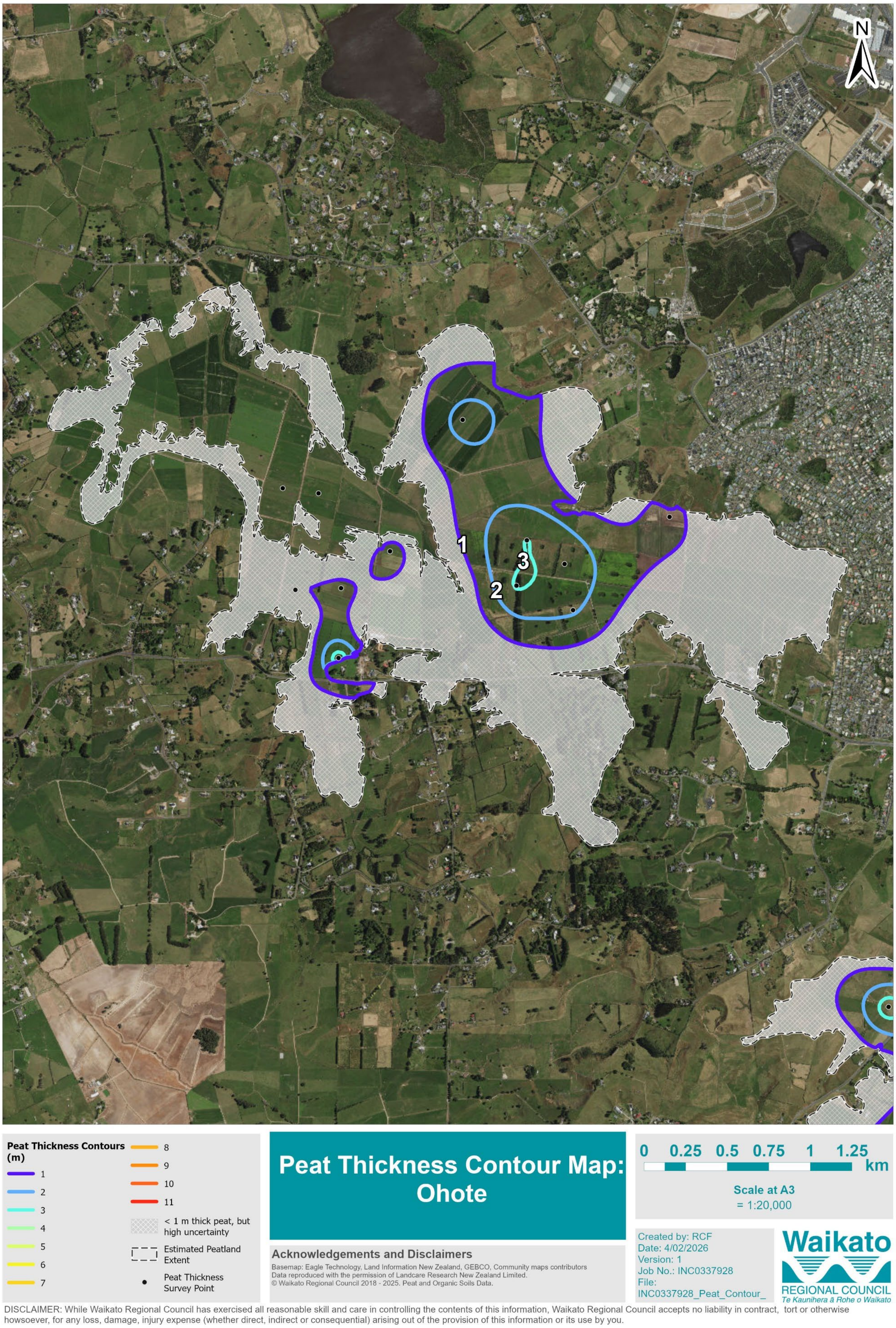


Figure 30. Map of Ohote showing interpolated peat thickness (metres) represented by coloured contour lines.

Ohote bog is a small peatland in the Waikato region, covering approximately 550–1,100 hectares. It consists of a narrow basin with shallow localised peat domes. Thickness reaches 3–4 m in the northeastern and southwestern sides of the bog, while other patches are shallow (<2 m), indicating disconnected peat formation.

The NW–SE transect spans ~4 km across the bog. Surface elevation ranges from ~20 m to 26 m above sea level (m asl), while base elevation dips to ~17 m asl in the centre, producing peat thickness of up to 3 m. The deepest peat occurs around 2 km from the NW end of the transect, where surface elevation remains around 22 m asl and base elevation is lowest (~17 m asl).

The SW–NE transect (~3 km) reveals a similar pattern, with surface elevation between ~20 m and 26 m asl and base elevation dipping to ~17 m asl in the centre. Peat thickness reaches 3 m in the deepest section, tapering to <1 m near the margins.

Ohote exhibits moderate peat deposits (relative to other bogs) concentrated in central depressions, with maximum thickness reaching around 3 m along both transects. Peripheral areas are dominated by thin peat (<1 m), indicating strong geomorphological control on peat formation.

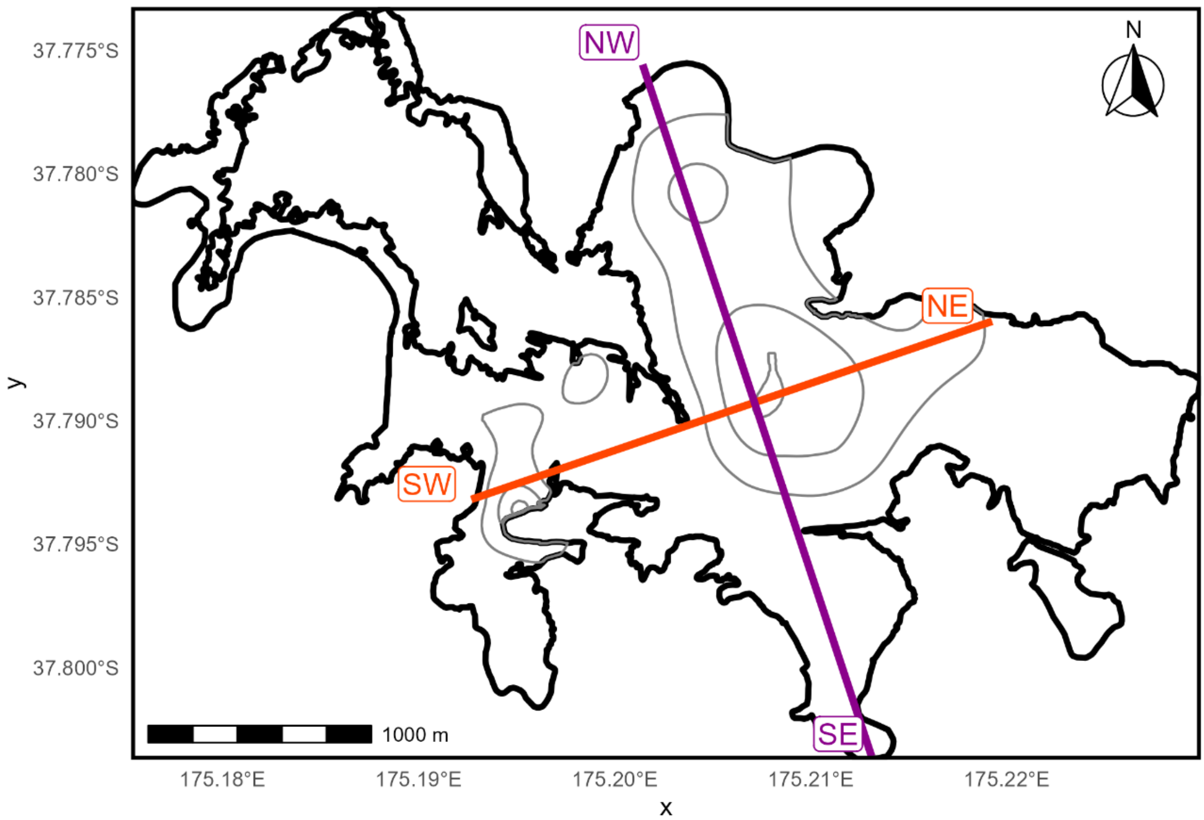


Figure 31. Ohote peatland showing the peatland boundary with thickness contour lines and the positions of the transects: northeast–southwest (purple) and southwest–northeast (orange).

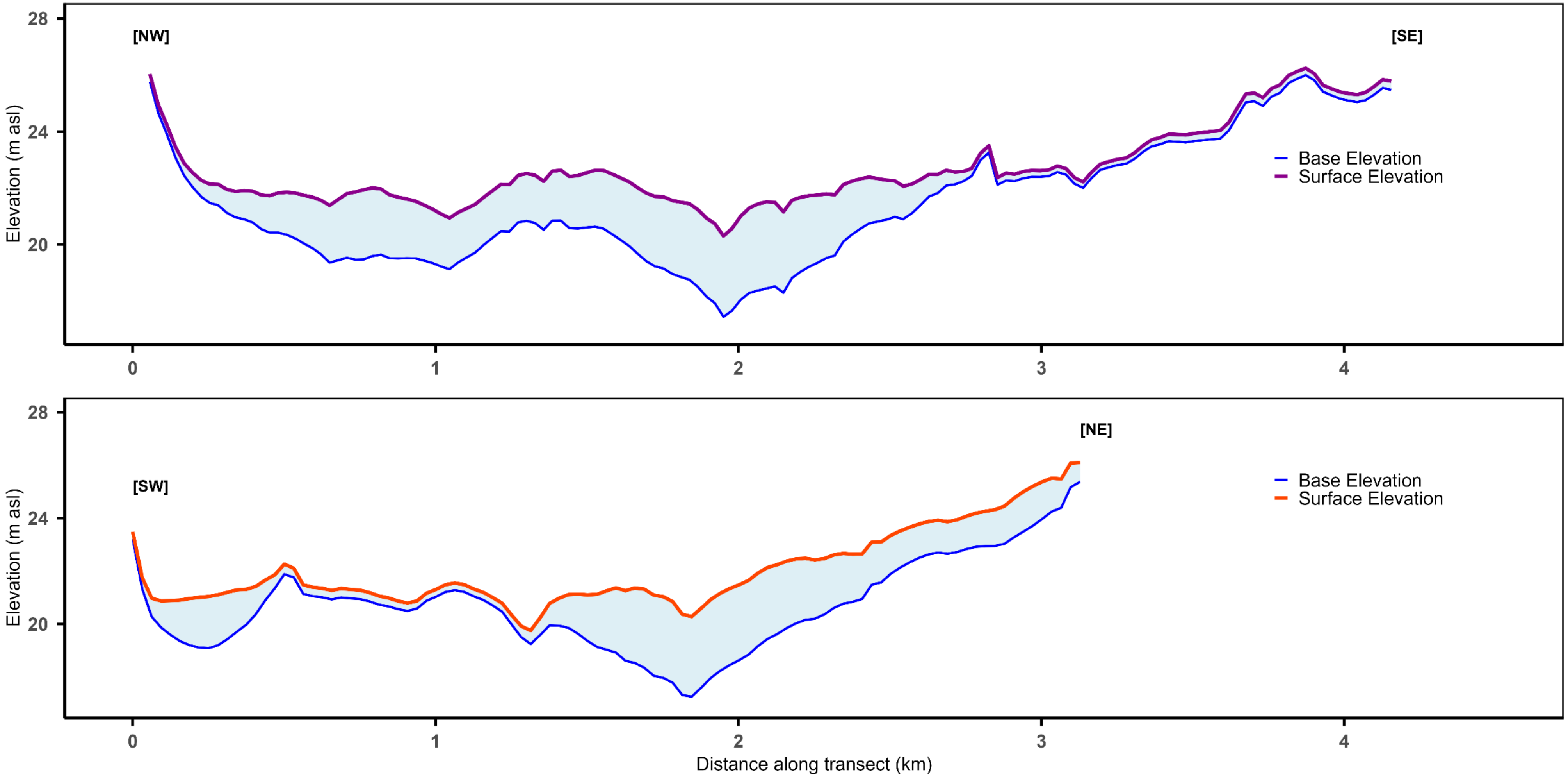


Figure 32. Elevation profiles plotted against distance of two transects across Ohote (location shown in Figure 31), with surface elevation (purple for northwest–southeast, orange for southwest–northeast) and peat base elevation (blue).

3.1.10 Orini

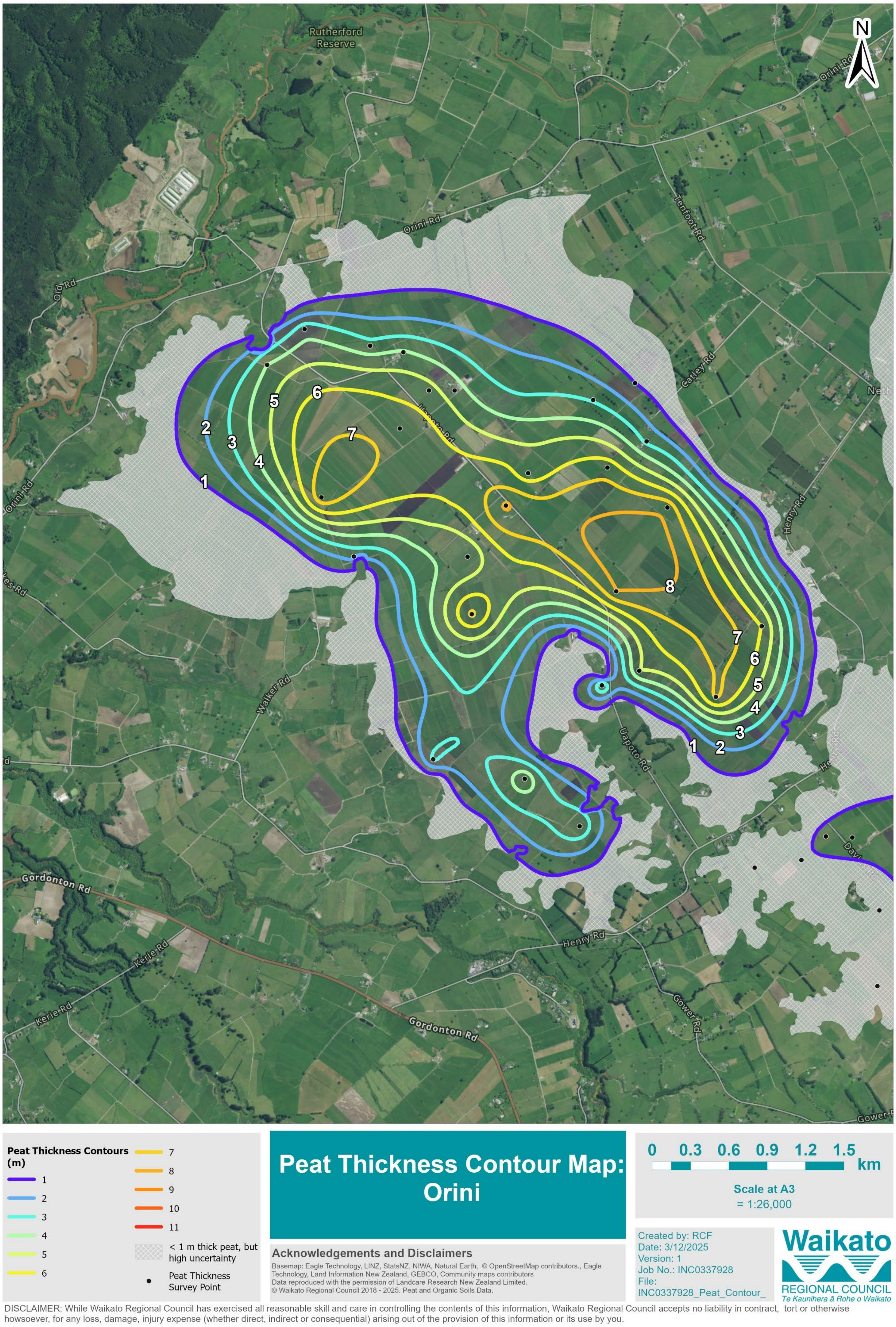


Figure 33. Map of Orini showing interpolated peat thickness (metres) represented by coloured contour lines.

Orini bog is a medium-sized peatland in the Waikato region, covering approximately 1,600–1,700 hectares. Orini shows a large dome with peat thickness exceeding 8 m in the centre. Contours indicate a gradual thinning toward the margins, suggesting a well-developed peatland with strong hydrological stability.

The N–S transect spans ~6 km across the bog. Surface elevation ranges from ~15 m to 29 m above sea level (m asl), with a sharp rise at the southern margin. Base elevation varies between ~13 m and 20 m asl, dipping in central sections to create peat thicknesses of 6–8 m. The deepest peat occurs between 2–5 km, where surface elevation remains around 20 m asl and base elevation is lowest (~13–14 m asl).

The NW–SE transect (~8 km) reveals a similar pattern, with surface elevation between ~15 m and 24 m asl and base elevation dipping to ~13 m asl in the centre. Peat thickness reaches 8 m in the deepest section, tapering swiftly to <1 m near the boundary. The profile suggests a broad peat dome with significant peat accumulation in the central basin.

Orini exhibits substantial peat deposits concentrated in central depressions. Peripheral areas of thin peat (<1 m) do not dominate the bog, indicating this deep basin has not been as constrained as other bogs by mineral ridges within the outer boundaries during peat formation. Both transects show thick peat in central, relatively flat areas where base elevation is lowest, with rapid thinning near the outer boundary as base elevation rises swiftly. Although moderate in spatial extent, the relative depth of the deposit highlights Orini as a zone of high peat accumulation.

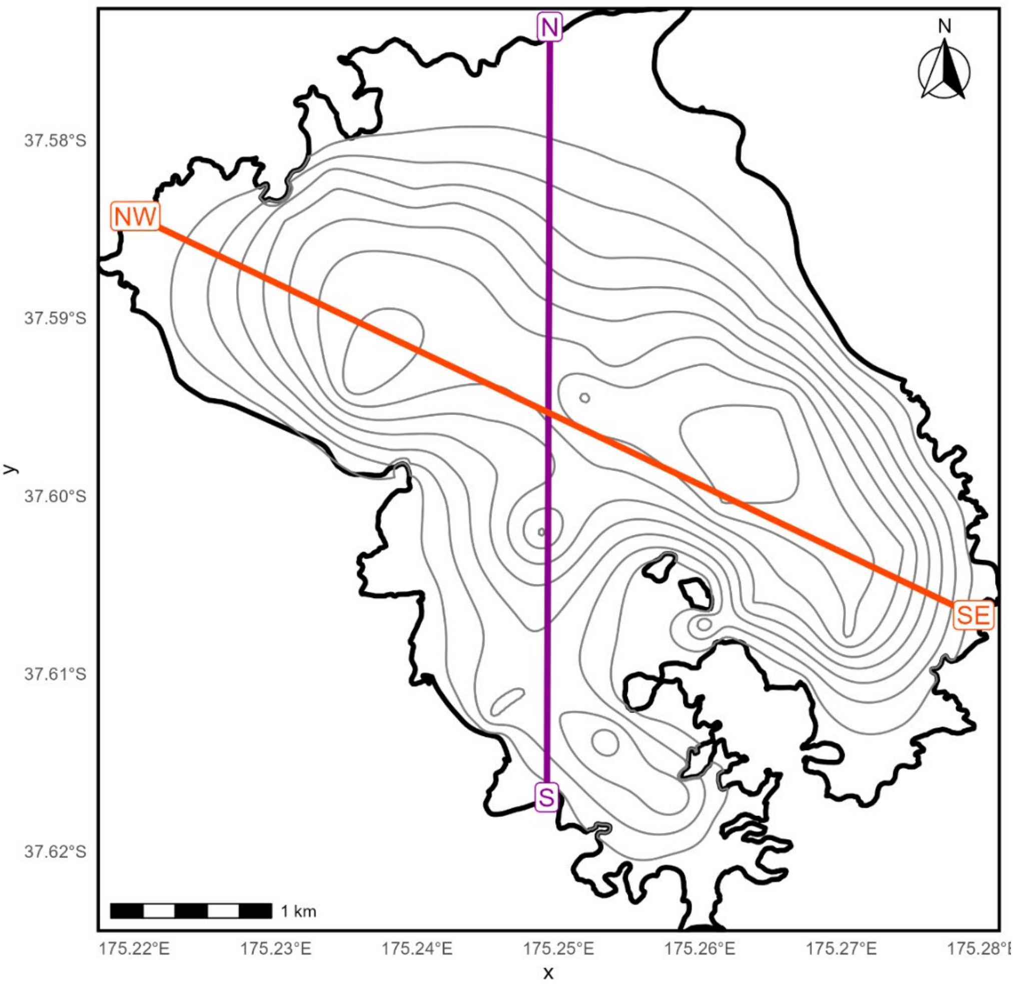


Figure 34. Orini peatland showing the peatland boundary with thickness contour lines and the positions of the transects: north–south (purple) and northwest–southeast (orange).

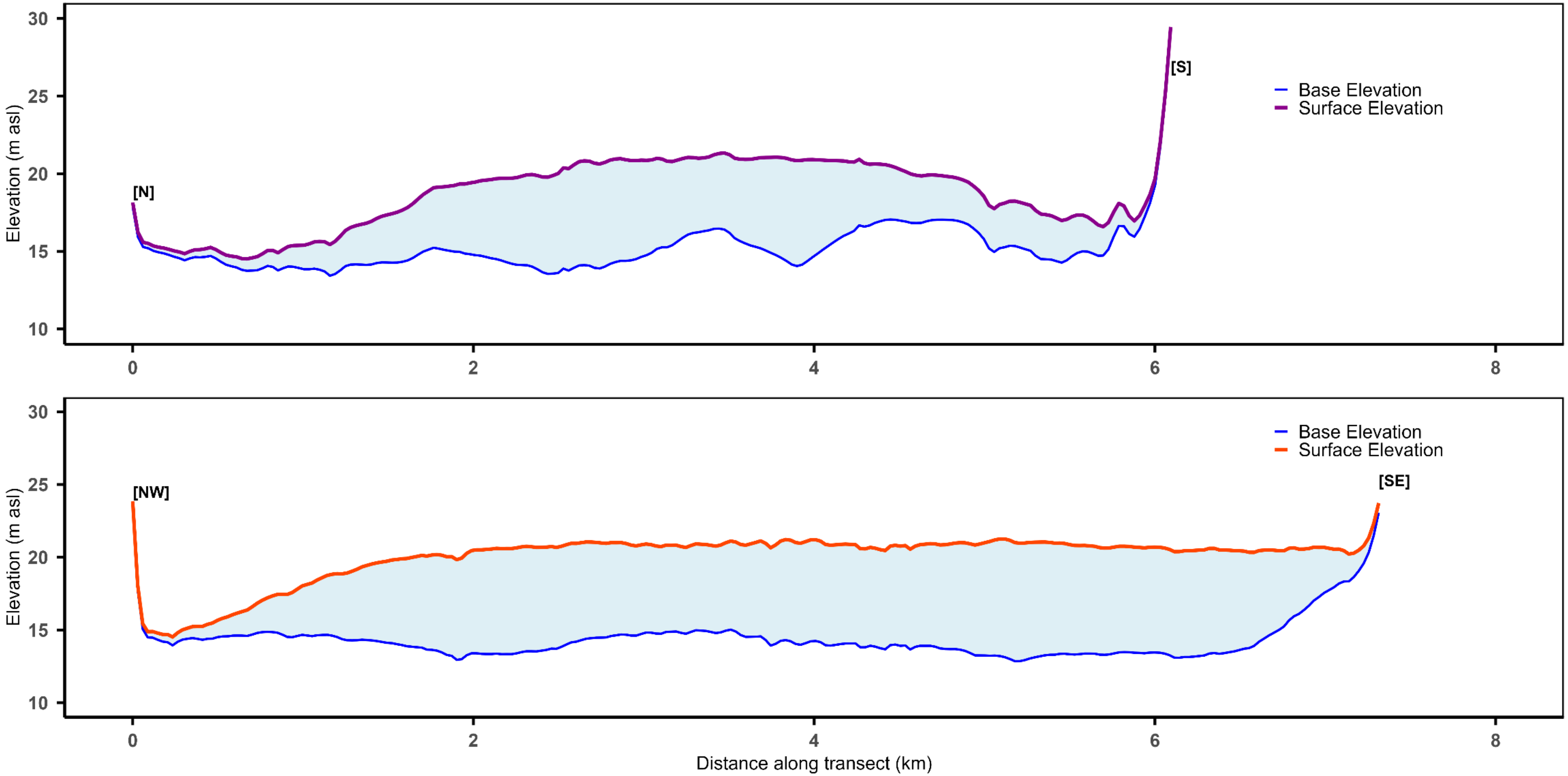


Figure 35. Elevation profiles plotted against distance of two transects across Orini (location shown in Figure 34), with surface elevation (purple for north–south, orange for northwest–southeast) and peat base elevation (blue).

3.1.11 Rukuhia

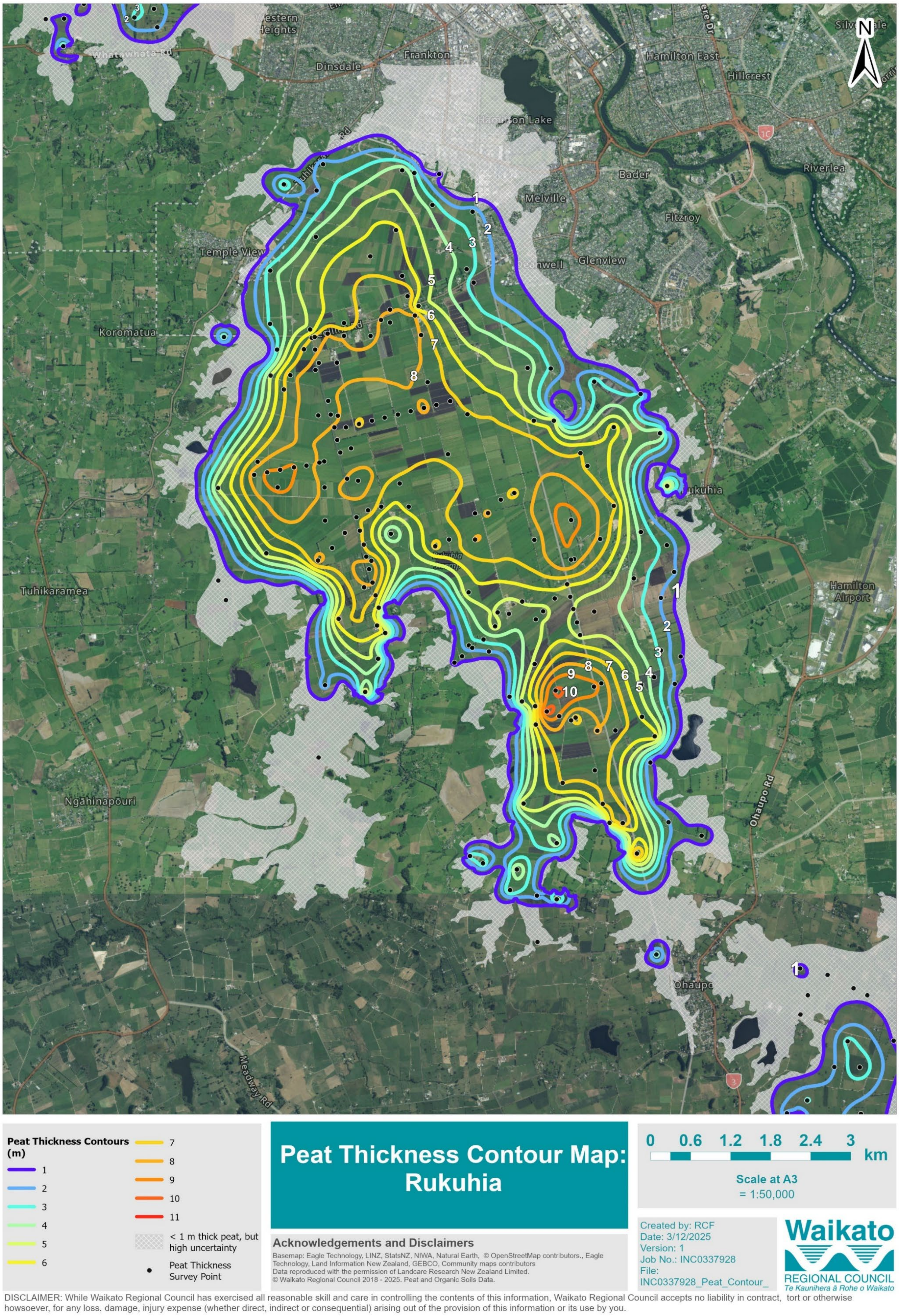


Figure 36. Map of Rukuhia showing interpolated peat thickness (metres) represented by coloured contour lines.

Rukuhia bog is a large peatland in the Waikato region, covering approximately 6,600 hectares. It is characterised by a broad, raised dome with limited shallow peat (<1 m) near the mineral soil boundary (similar to Orini). Peat thickness across the Rukuhia peatland shows a clear spatial gradient, with the interpolated contours indicating the thickest deposits in the southern lobe (up to 10 m thick) and central parts of the bog (up to 9 m thick). Uncertain (low confidence hashed) areas with less than 1 m of peat are most obvious near the northern and southeastern lobes where the northern lobe was unmapped during this survey (urban area) and the southwestern lobe only has one site to represent a complicated area (e.g., surrounding hills). This distribution reflects a central basin morphology influenced by historical drainage impacts, with thick peat persisting in the centre and progressive thinning toward the margins.

The W–E transect spans ~10 km across the bog. Surface elevation ranges from ~42 m to 63 m above sea level (m asl), with a sharp rise at both the eastern and western margins. Base elevation varies between ~38 m and 46 m asl, dipping throughout the central section to create peat thicknesses of 8–9 m.

The northwest–southeast transect (~17 km in length) spans a greater elevation range and shows a more gradual slope compared to the west–east transect, but reveals a similar pattern, with surface elevation between ~35 m and 57 m asl and base elevation dipping to ~32 m asl in the centre. Peat thickness reaches 9.5 m in the thickest section and rapidly tapers to <1 m at the boundary. The profile suggests a broad peat dome with significant peat accumulation in the central basin.

Rukuhia exhibits substantial peat thickness in central areas. The deepest peat occurs near the centre of the peatland where surface elevation is relatively flat and base elevation is lowest. Like Orini, peripheral areas of thin peat (<1 m) do not dominate the bog, suggesting this extensive area has a deep basin that has not been geomorphologically constrained by mineral ridges within the outer boundaries during peat formation. The large size and thickness of the deposit make Rukuhia a significant peat resource among Waikato peatlands.

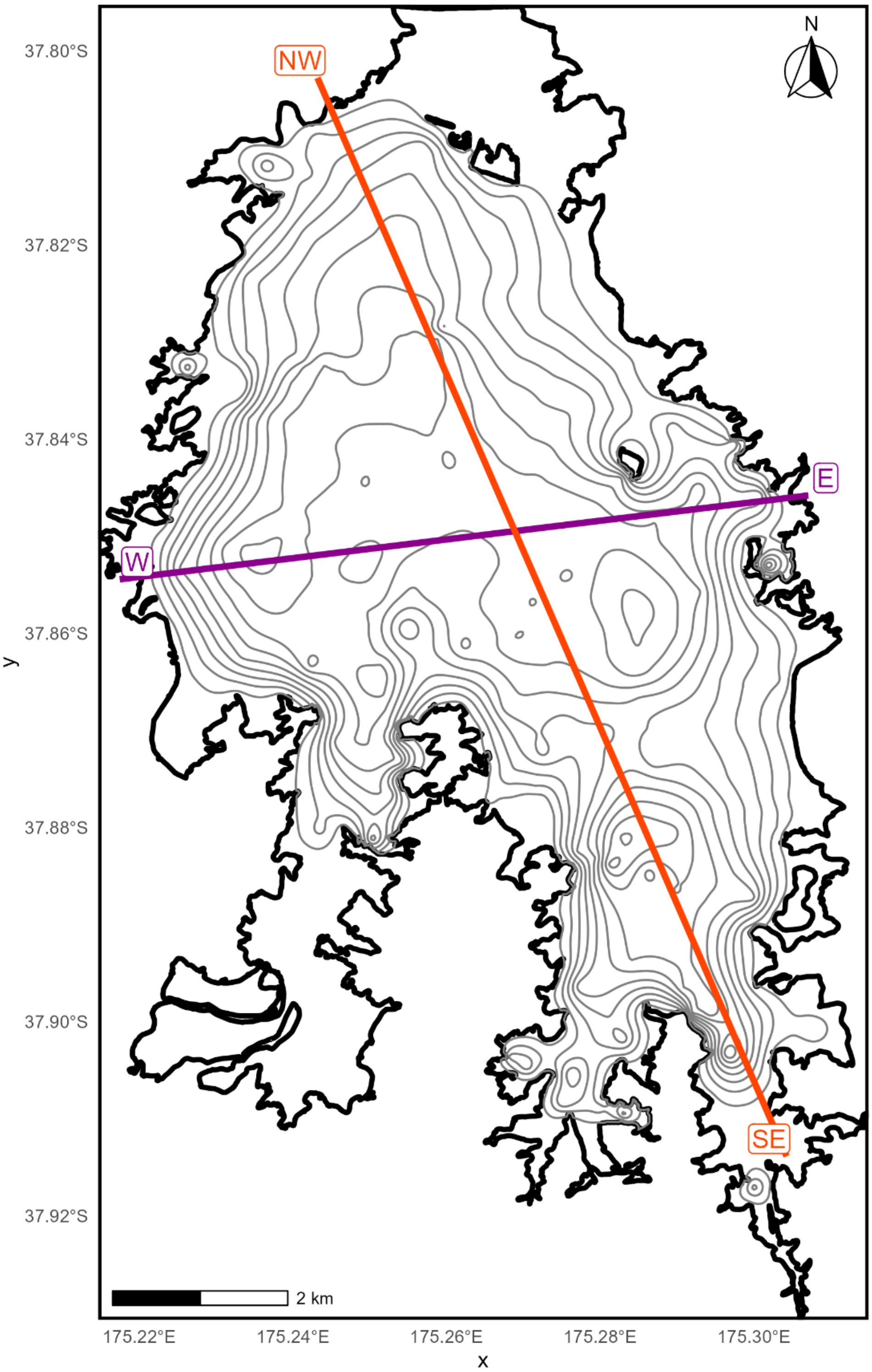


Figure 37. Rukuhia peatland showing the peatland boundary with thickness contour lines and the positions of the transects: west–east (purple) and northwest–southeast (orange).

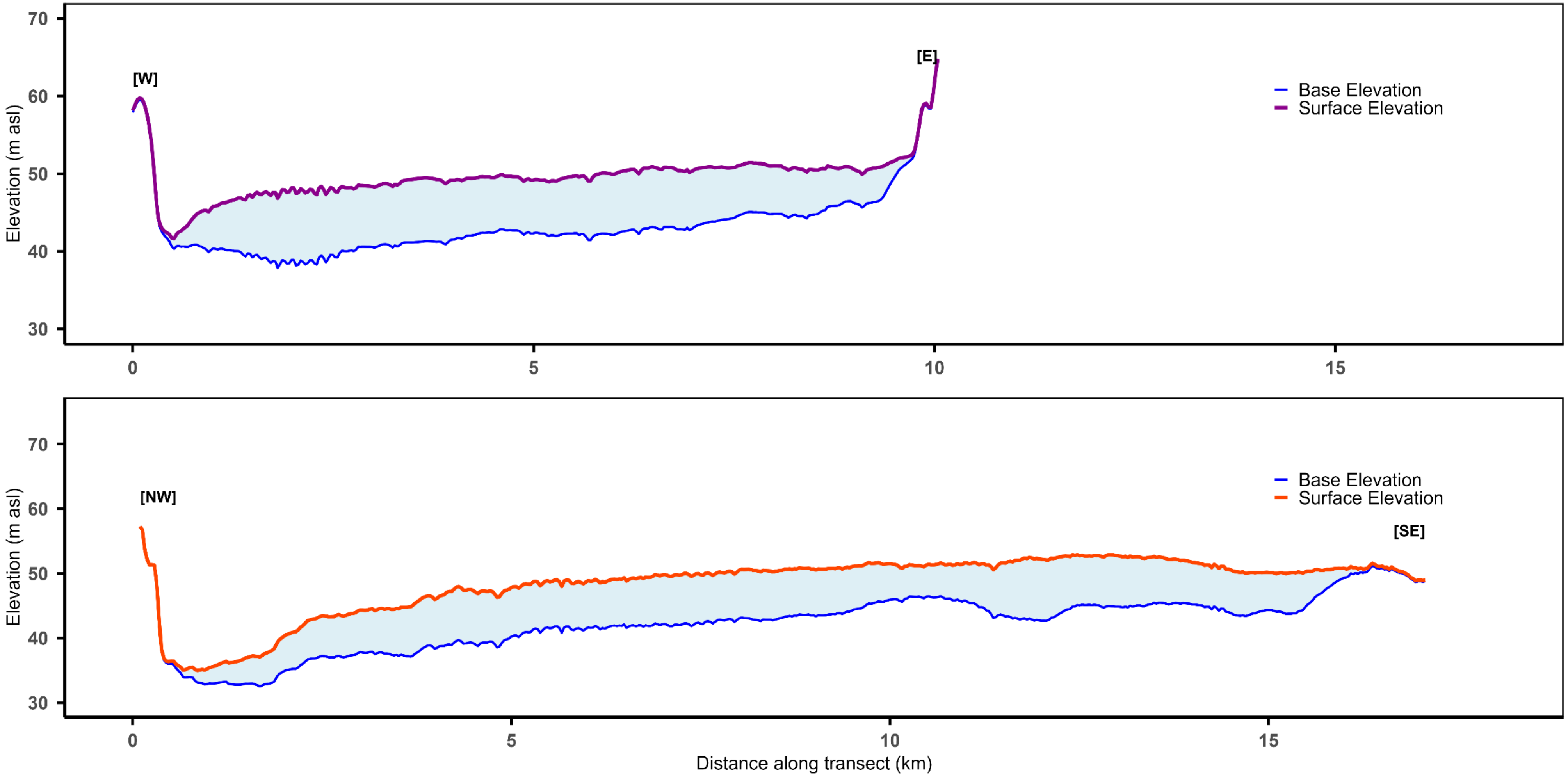


Figure 38. Elevation profiles plotted against distance of two transects across Rukuhia (location shown in Figure 37), with surface elevation (purple for west–east, orange for northwest–southeast) and peat base elevation (blue).

3.1.12 Te Mimiha

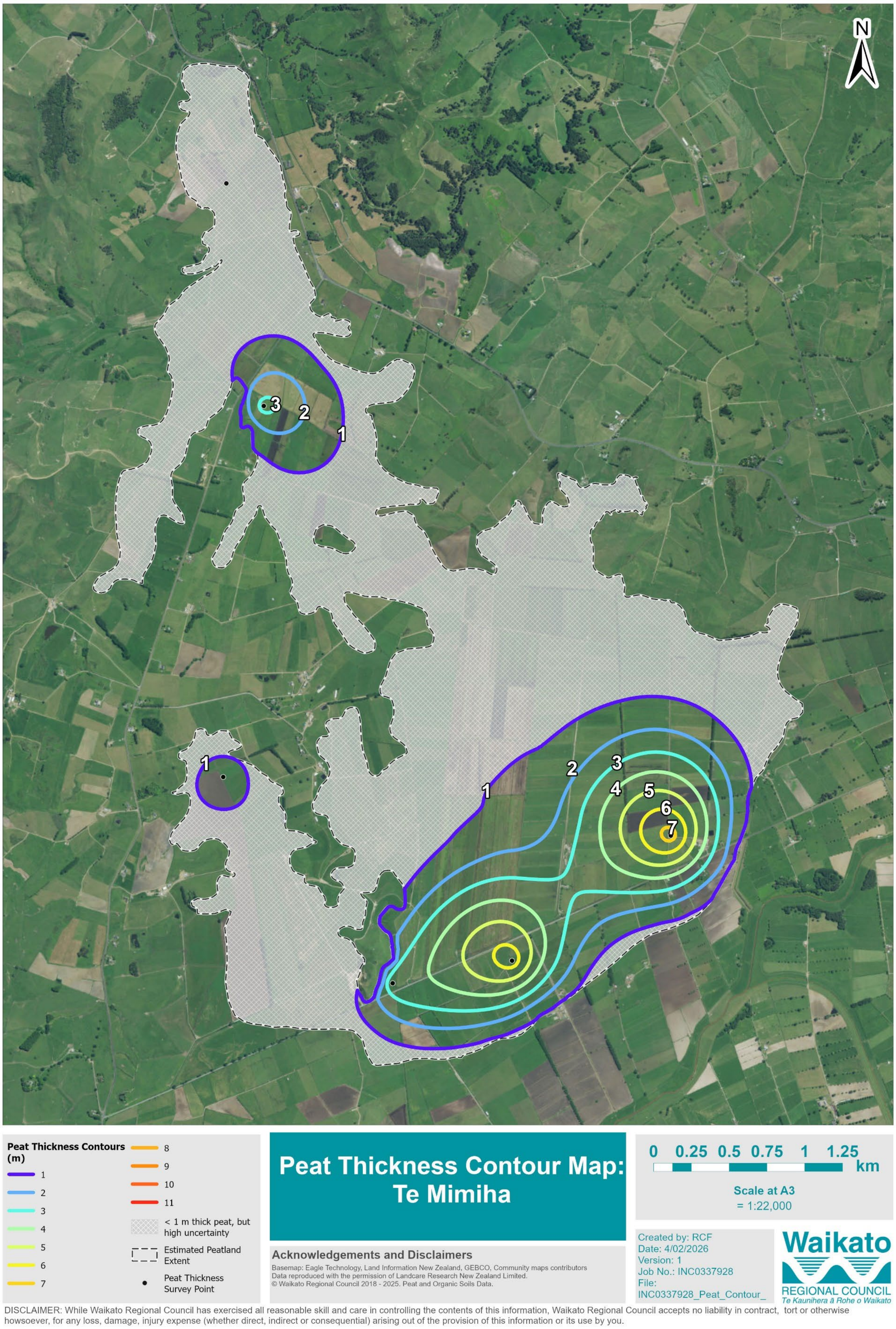


Figure 39. Map of Te Mimiha showing interpolated peat thickness (metres) represented by coloured contour lines.

Te Mimiha bog is a small peatland with a few isolated deep deposits, covering approximately 900–1,300 hectares. The largest dome in the southeast contains the thickest peat, reaching 8 m in the centre according to the model. Although measurements suggest the thickest site was 11.8 m. Thickness gradually decreases outward towards the margins with a significant area of shallow peat (<1 m) dominating the bog. There is also a small deposit of peat up to 3 m thick in the north, indicating disconnected peat formation across the landscape. Despite the small area, the bog has a volume of 0.01 km^3, reinforcing that the bog has very deep peat deposits. However, with few sites visited across this bog, it is difficult to draw any robust conclusions from the contours produced by the model and for this reason, transects were not presented across Te Mimiha. Field notes indicate sampling difficulties at this location due to woody obstructions and the base of the peat was not always conclusively reached.

4 Discussion

4.1 Spatial patterns and geomorphological controls

Peat thickness across the Waikato peatlands reflects the combined influence of macrotopographic controls, including basin morphology, dome formation, regional hydrology, climate patterns, dominant plant communities and microtopographic controls, including substratum type, vegetation, biogeochemical cycles, localised hydrology, and drainage history (Clymo 1984; Belyea and Baird 2006; Silvestri et al. 2019; Cobb et al. 2024; Li et al. 2024). Macrotopography primarily drives inter-bog differences, determining why large basins host thicker domes, while microtopography controls intra-bog variability, shaping local thickness gradients, hummock-hollow patterns, and edge thinning within individual peatlands. These controls operate over different spatial scales and timescales: macro factors set the long-term template for peat formation and maximum thickness, whereas micro factors, including human-induced changes to hydrology, vegetation, and land use, modify thickness patterns more recently and locally. The following subsections examine how these natural and anthropogenic influences have encouraged or limited peat accumulation across the Waikato.

4.1.1 Natural formation drivers

Peat thickness in undisturbed Waikato peatlands reflects the cumulative effect of organic matter accumulation under waterlogged conditions over thousands of years. This process is governed by a hierarchy of controls operating at different spatial scales.

4.1.1.1 Inter-bog thickness comparison – differences in peat thickness across bogs

At the regional scale, macrotopography (basin topography) are the dominant controls on inter-bog thickness differences. Substratum topography and elevation are influential factors, with thicker deposits forming on footslopes, shoulders, and summits. Low-lying basins with minimal relief and stable hydrology allow thick peat domes to develop, while higher or sloped terrain limits accumulation (Glaser et al. 1990; Maggs 1997; Sun et al. 2023; Cobb et al. 2024). Substratum material further influences water retention, for example, clay and silt bases sustain higher water tables than sand bases, reducing drawdown-induced oxidation (Gatis et al. 2019). Vegetation type and productivity also matter because ombrotrophic systems dominated by restiad species (Empodisma/Sporadanthus) promote peat formation under nutrient-poor, rainfed conditions (Clymo, 1984; Belyea & Baird, 2006).

New Zealand wetland history indicates many wetlands began forming after the Last Glacial Maximum (~18,000 cal. yrs BP), with a strong linear trend of initiations since 14,000 cal. yrs BP driven by geomorphic processes (e.g., river course changes) (McGlone 2009). The Waikato peatlands occupy fault-bounded lowland basins infilled by volcanogenic and alluvial deposits, with antecedent channels of the ancestral Waikato River and widespread post-Hinuera floodplain surfaces providing the templates for peat development (Johnson and Gerbeaux 2004; McGlone 2009; Lowe 2010; Denyer and Robertson 2016). Peat cores collected from Kopuatai suggest that marine conditions existed in this inland region of the Hauraki Basin. Naish (1990) theorised that as the sea level receded, peat formed across the basin and the Waihou River migrated across the western Hauraki plain over marine mud and alluvial sediments (Naish 1990). Peat within Kopuatai Peat Dome reaches ~14 m thick in places, with the base 4–7 m below sea level and the dome crest ~5 m above sea level according to Selby & Lowe (1992). This reflects the results demonstrated by the cross-sectional transects for Kopuatai (Figure 14). Recent theory and observations confirm that domed morphology emerges from universal water table feedbacks because peat cannot rise indefinitely without drying and decomposing, thus producing characteristic mound shapes globally (Cobb et al. 2024).

4.1.1.2 Intra-bog thickness variability – spatial and topographic controls within bogs

Within individual bogs, microtopography and local terrain attributes dominate thickness patterns. Local elevation gradients, from the bog centre to margins, strongly influence water table position with central depressions being wetter and accumulating thicker peat, while higher margins tend to be drier and thinner (Belyea and Baird 2006). Hummock-hollow microtopography adds small-scale heterogeneity in moisture, microbial activity, and bulk density, influencing soil organic carbon (SOC) stocks and greenhouse gas (GHG) emissions (Belyea and Baird 2006). Subsurface lithology further regulates thickness as clay-rich horizons retain water, whereas silty horizons on upper slopes drain freely, limiting peat thickness (Henrion et al. 2024). According to Li et al. (2024), topographic and vegetation factors explain 27% of peat thickness variability, indicating that a large proportion of the remaining variability likely reflects the influence of subsurface properties, hydrological processes, and small-scale spatial heterogeneity. However, these interacting controls are not fully captured by surface predictors and vary across scales.

Peatland form reinforces these patterns. Large, continuous raised bogs (e.g., Hauraki, Rukuhia, Moanatuatua) display coherent thickness gradients and thick centres (>8–10 m), whereas disconnected systems (e.g., Huntly complex, Kainui) remain less than 2–3 m thick and exhibit irregular patterns interrupted by mineral ridges and open water, reflecting limited hydrological connectivity and stronger topographic or anthropogenic constraints (Cobb et al. 2024).

Multi-scale studies (i.e., using ground penetrating radar (GPR), electromagnetic induction (EMI), airborne electromagnetic (AEM), and electrical resistivity imaging (ERI)) confirm that macrotopography provides the template for thickness gradients, while microtopography and vegetation features add local heterogeneity (Parry et al. 2014; Comas et al. 2015; Silvestri et al. 2019). Our transects reflect these patterns of deep centres over subsurface depressions and thin margins over subsurface highs where the peat meets mineral soils.

4.1.2 Anthropogenic modification

While natural geomorphology and hydrology provide the framework for peat growth and resulting thickness, human modification can reshape these patterns by lowering water tables, fragmenting domes, and accelerating oxidation under different management systems (Li et al. 2024).

Over 80% of the Waikato peatland area has been drained during the past century (Pronger et al. 2014; Wheatley-Wilson and Wyatt 2024). Artificial drainage lowers the water table, accelerating oxidation and subsidence that progressively thins the peat (Pronger et al. 2022). This loss is particularly evident around bog margins, where progressive thinning no longer qualifies the remaining peat as an Organic Soils (<30 cm cumulative organic soil material in the top 60 cm; Hewitt, 2010). The thin peripheral areas and irregular thickness patterns observed in our profiles suggest a history of drainage and agricultural conversion, as well as the effects of current land use management practices. Over time, land use change, drainage, and agricultural development have fragmented continuous domes into smaller remnants, reducing hydrologic connectivity and limiting thickness. Naturally small and disconnected systems (e.g., Huntly (Figure 18) & Lower Waikato (Figure 25)) are even more vulnerable to these effects. Intact remnants such as Kopuatai Peat Dome contrast with heavily modified systems like Komakorau, Moanatuatua, Rukuhia, and Hauraki, where canalisation and drainage have degraded the peat and decreased the total area of Organic Soils (Davoren 1978; Pawson and Brooking 2013; Lambie and Ratcliffe 2020).

Historical records show widespread drainage and fire following initial forest clearance to expand agricultural land has caused severe degradation of peat systems (Selby and Lowe 1992; McGlone 2009; Pawson and Brooking 2013; Minasny et al. 2024). Today, drainage and land use management practices continue to drive peat loss through GHG emissions and subsidence (Hiraishi et al. 2014; Pronger et al. 2022). Fire also poses a threat to surface peat and vegetation, so while it may not cause subsidence, it reduces thickness locally, releasing GHG emissions, and altering carbon and nutrient status (Wilkinson et al. 2020). Recent Whangamarino burn assessments noted limited deep peat combustion due to high pre-fire water levels but significant vegetation loss, underscoring how management influences resilience (Wilkinson et al. 2020; Department of Conservation 2025). While fire is generally localised, subsidence tends to impact the entire drained system from paddock to farm and sometimes up to catchment scale. The dominant controls on subsidence include time since drainage, temperature, drainage depth and land use intensity, and peat thickness (Pronger et al. 2014; Pronger et al. 2022; Seidel et al. 2025). To minimise the effect of subsidence, global literature suggests rewetting and hydrological restoration may be a means of reducing emissions and subsidence (Goodrich et al. 2025). Mitigations such as drainage management and reduced cultivation practices may also help reduce subsidence (Pronger et al. 2022). All these processes alter the thickness of the peat deposit in some way, although it is difficult to understand which process has affected a certain area by looking at peat thickness contours alone.

4.1.3 Peat thickness in the international context

Peat-thickness studies are widespread internationally (Europe, Canada, Indonesia, Congo Basin) and commonly combine field coring with geophysical methods (GPR, EMI, AEM, ERI) and digital soil mapping to predict thickness and strengthen confidence in thickness models (Adetsu et al. 2024; Li et al. 2024; Skye et al. 2025).

Typical international temperate peatlands often average ~1–3 m thickness across large complexes, with local maxima of >5–10 m in raised bogs (Evans et al. 2022; Cobb et al. 2024). Li et al. (2025) estimated mean peat thickness to be 1.8 m (90% between 0.9–2.6 m) based on mapping at a site in Canada. Other international studies similarly report mean thickness of ~1–1.5 m, noting sampling biases and the need for comparable datasets (Comas et al. 2015; Beucher et al. 2020; Skye et al. 2025). Skye et al., (2025) presents the Peat-DBase, which is a harmonised, quality-controlled global compilation of measurements of the base of the peat and reports median thickness as 1.3 m (IQR: 0.6–2.4 m) from 204,902 measurements across the globe. Waikato peatlands are generally thicker than those reported internationally, with several sites having mean and maximum peat thicknesses that exceed commonly reported global averages (Table 3). One third of our Waikato peatlands exceeded the international thickness averages between 1–3 m, including Moanatuatua (3.7 m), Hoe o Tainui (5.4 m), Orini (5 m), Rukuhia (6 m), and Te Mimiha (8 m). Likewise, Waikato systems with local maxima above the 5–10 m range include Komakorau (10.5 m), Moanatuatua (11 m), Rukuhia (11.1 m), Te Mimiha (11.8 m), and Kopuatai (12 m), but some of these sites are considered outliers in comparison to the data from the rest of the bog.

Table 3. Comparison of Waikato and some internationally reported peatland thicknesses.

Comparison category	International literature	Waikato peatlands
Typical mean/average thickness	~1–3 m (Comas et al. 2015; Beucher et al. 2020; Evans et al. 2022; Cobb et al. 2024; Skye et al. 2025)	One-third of sites exceeded 3 m mean thickness
Reported mean thickness	1.8 m (~0.9–2.6 m; Li et al. 2025)	Moanatuatua 3.5 m; Hoe o Tainui 4 m; Orini 4.6 m; Rukuhia 5.7 m; Te Mimiha 6.2 m
Global median thickness	1.3 m (IQR 0.6–2.4 m; Skye et al. 2025)	Several Waikato peatlands exceed the upper quartile and median values by more than two-fold
Typical maxima in raised bogs	>5–10 m (Evans et al. 2022; Cobb et al. 2024)	Komakorau 10.5 m; Moanatuatua 11 m; Rukuhia 11.1 m; Te Mimiha 11.8 m; Kopuatai 12 m

Note: the comparison in this table is intended to provide indicative international context for the Waikato peat thickness results and does not represent a full literature review of global peat thickness studies.

Waikato systems seem to show thicker peat deposits than reported internationally, however, underestimates from the global literature may also be related to limited data and how the models predict thickness. Much like the kriging model used to create our contour maps, other studies in the literature show their models also consistently underestimate peat thickness. For example, Adetsu et al. (2024) contains information from New Zealand peatlands but still underestimates the thickness (0.5–3 m thick). These underestimates are likely due to the combination with Australian peat data and poor model predictions given non-uniform data point distribution and insufficient data for modelling.

4.2 Methodology review/limitations

The collection of good peat thickness data underpins accurate peat maps and more generally, informs peat resource information (Parry et al. 2014; Beucher et al. 2020). Several challenges arose over the course of this project, particularly during the fieldwork and mapping components of this work, that reduced confidence in our data. During the survey, field confidence varied across bogs due to (i) obstructions that occasionally prevented full penetration to the mineral substrate; (ii) difficulty determining the occurrence of the base; and (iii) physical strain limitations. As a result of the difficulty in obtaining data, this affected the quantity and quality of data going into the models used to create the contour maps. These factors (e.g., low sampling density) reduce statistical confidence and increase uncertainty in interpolated thickness surfaces. This section covers the level of confidence we have in our data, limitations of our sampling and mapping techniques, comparison of the accuracy and applicability of other techniques, and recommendations for future studies.

4.2.1 Physical sampling techniques

4.2.1.1 Confidence and limitations

As described in sections 2.2 & 2.3, we used a specific sampling design and methodology to determine peat thickness and surface elevation for over 800 sites during the 2023 survey. This methodology was similar to the methods of the other studies whose data was used for mapping (Table 1) (Palmer and Hainsworth 2012; Pronger et al. 2014; Hill et al. 2020). This method allows penetration to the firm mineral substrate, but sampling confidence varied due to frequent obstructions caused by buried wood and other impenetrable layers. Obstructions were more common in some bogs than others (e.g., Rukuhia), and partial penetration increased friction and retrieval effort. These issues meant the substratum was not always determined at all five points per site, lowering confidence where only one or two successful hits of the peat base were achieved. Figure 40 shows how many times (up to 5 using the 5-point method described in section 2.2.1) that the peat base detection was successfully achieved during the 2023 survey. The 2023 survey attempted up to five points per site, whereas most prior studies relied on single-point probing, apart from the 2012 and 2019 surveys by Pronger et al. (2014, 2020). It appears that despite these difficulties, 5 points were successfully achieved at most sites. The multi-point probing method improves confidence in detecting the base of the peat compared to single-point methods used in other surveys, despite a longer time requirement.

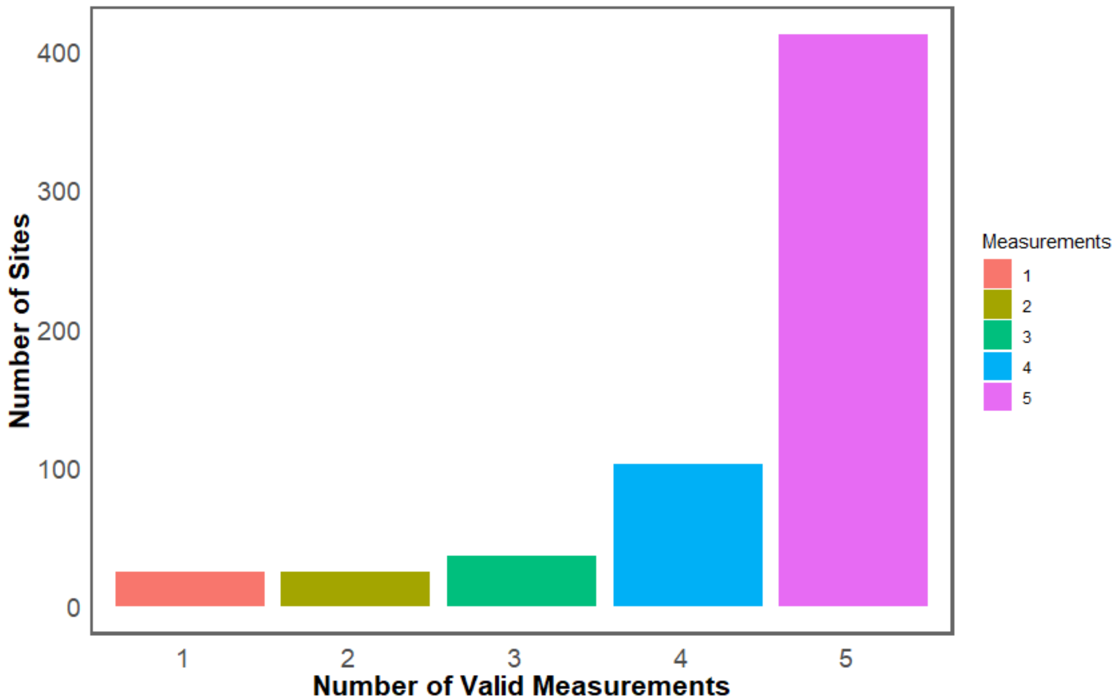


Figure 40. Distribution of sites by number of valid peat thickness measurements (excluding sites <0.3 m).

Alongside underground obstructions, determining the base proved difficult in some locations due to an inability to detect the change between peat to soft silt layers deeper in the profile. Material recognition proved challenging using the probe as fine silts can rub off the drill-bit, obscuring identification, whereas sand or clay tend to adhere and are easier to detect by feel (Palmer and Hainsworth 2012).

These physical challenges made probing labour-intensive and time-consuming, often requiring use of the extraction tools (section 2.3.3) to reduce operator strain. Physical challenges are also echoed in the literature (Gatis et al. 2019; Beucher et al. 2020; Adetsu et al. 2024; Li et al. 2024). While successful in their role, the two extraction tools we used both had their own limitations including portability and the load-bearing capacity.

4.2.1.2 Other techniques for measuring peat thickness

Manual probing is the most widely used technique for peat thickness measurement because it is simple, low cost, and is an effective bottom-up method of collecting small, paddock-scale data (Parry et al. 2014; Adetsu et al. 2024). However, it is a time-consuming and physical task in which accuracy can be compromised by woody obstructions and soft silt layers. There is also the potential for subsurface curvature of the rod causing depth overestimation (Parry et al. 2014; Beucher et al. 2020; Li et al. 2024).

At larger scales, remote sensing and digital soil mapping can delineate peatland extent and infer thickness patterns, while geophysical methods such as ground penetrating radar (GPR), electromagnetic induction (EMI), airborne electromagnetic (AEM), and electrical resistivity imaging (ERI) methods enable non-invasive, high-resolution mapping of the peat–mineral interface, though calibration and ground-truthing are essential (Parry et al. 2012; Parry et al. 2014; Silvestri et al. 2019; Beucher et al. 2020; Adetsu et al. 2024; Li et al. 2024).

Parts of the Waikato region have been mapped with LiDAR, InSAR, and radiometric survey. Although not specifically meant for mapping peat, LiDAR improves elevation and terrain modelling but also requires robust ground data for validation (Pronger et al. 2019; Pronger, Price, et al. 2021; Pronger, Glover-Clark, et al. 2021), while radiometric data is restricted to responses from the top 30 cm of the ground and maps the location of water (no radiometric response) (Cooper 2008). InSAR, in combination with DEMs, has been used in the region to identify peatlands and estimate subsidence, but fading signal effects or phase bias may overestimate rates (Harvey and Rissmann 2025).

Combining datasets, as done in this survey by integrating historic thickness sites and well data, improves spatial coverage and model reliability (Parry et al. 2014). Combining both manual probing and other geophysical and remote sensing techniques would provide a more comprehensive dataset. It is also important to note that all techniques benefit from careful calibration and cross-validation, and future work should prioritise integrating data captured using these methods with surface elevation data to reduce reliance on intensive physical probing (Monteverde et al. 2022; Adetsu et al. 2024).

4.2.1.3 Recommendations for measuring peat thickness

Future surveys should prioritise using the surface elevation data collected in this campaign to monitor subsidence and peat thickness change, reducing the need for intensive peat thickness probing. Repeat measurements of surface elevation at the same sites will enable accurate subsidence calculations and therefore recalculation of the peat resource, saving time and physical effort. Confidence in thickness estimates improves with multi-point sampling, so the 5-point method remains best practice where both probing and surface elevation measurements are required. Geophysical techniques such as GPR or ERI should be incorporated for detection of the base of the peat, calibrated against ground-based hits. Additionally, improving knowledge of historic substratum conditions (e.g., clay or sand layers) will help anticipate probing challenges and refine future modelling approaches.

4.2.2 Mapping methods

4.2.2.1 Confidence and limitations

Peat thickness was modelled using contour mapping created from kriging, constrained by boundary refinement methods in R and ArcGIS Pro, and supported by LiDAR-derived elevation data (for all geospatial layers used in this study, see Appendix L – GIS layers). Kriging interpolation was applied to generate continuous surfaces from site measurements. While these techniques are robust, mapping accuracy is inherently limited by the density and distribution of measurement sites, particularly in bogs with sparse data (e.g., n = <10) such as Te Mimiha, where few observations limit contour prediction accuracy and increase uncertainty. Contours for these bogs should therefore be regarded as indicative representations of peat thickness patterns rather than definitive spatial predictions. Additionally, the use of LiDAR improves elevation modelling and can be used for future subsidence comparison, but it does not directly measure peat thickness, reinforcing the need for combined techniques.

The peat thickness sites and contour maps compiled by Davoren (1978) provide a valuable reference for assessing changes in peat extent. However, because these data were originally in hard copy format, they required scanning, orthorectification, and integration into a GIS database for comparison with contemporary measurements from the 2023 survey. As a result, the historic dataset carries inherent limitations, and the derived historic estimates should be regarded as approximate rather than precise. Data collected during the 2023 survey are also not intended to be compared with historical depth from Davoren for the calculation of subsidence due to the high uncertainty. Future work could complement the existing point network by filling gaps in spatial coverage using a statistically informed approach (e.g. random or stratified site selection informed by peatland extent and historical thickness), improving peatland representativeness while maintaining comparability with historic survey locations should the original survey data become available.

Thickness contour surfaces are interpolated from discrete observations and therefore show generalised trends rather than exact expressions of local thickness. Although displayed on a fine-resolution grid, the level of detail supported by the model is constrained by the density and distribution of measurement sites. As previously discussed, interpolation accuracy depends on sample density and bog geometry. Sparse or irregular site distributions smooth out microtopography and may misrepresent local depressions, ridges, or boundary transitions. The scale at which the peat extent was mapped, and number and density of samples control the level of detail: at coarse scales, the model does not readily predict fine hummock–hollow relief, so contours should be interpreted as generalised patterns. Contours are also constrained by a boundary, so it is crucial that the boundary is correct to inform the modelling of contours to support accurate volume calculations and clearer maps. In addition, the 5-point sampling design was intended to provide a representative site mean rather than quantify metre-scale variability, so measurements were averaged prior to modelling. Future surveys could incorporate nested or clustered sampling at selected sites to better characterise short-range variability.

Comparison of measured and modelled peat thickness statistics demonstrated that the contour model systematically underestimated peat thickness across most bogs. On average, modelled mean and median peat thicknesses were 58% and 74% lower than measured values, respectively, while modelled maximum thicknesses were only 19% lower than measured maxima. This suggests that the model generally captures the location and magnitude of deep peat centres but predicts a greater proportion of shallow peat across the peatland surface. Although this bias is consistent with the tendency of kriging-based models to underestimate or 'smooth' thickness values, it is likely partly attributable to the inclusion of non-peat observations (<0.3 m) in the modelling dataset, which were excluded from the measured summary statistics in Figure 10. In some peatlands, non-peat sites comprised more than half of all observations, creating a strong bias towards shallow peat thicknesses within the modelled dataset. Consequently, peat volume estimates may be slightly conservative, particularly in bogs containing isolated areas of unusually thick peat. Regardless, inclusion of these observations is necessary because they contribute to the contour generation process and represent realistic peatland boundaries and transitions to mineral soils.

Model performance was strongest in large, well-developed peat domes such as Kopuatai, where bog morphology is well defined and site density is relatively high (>100 sites). In smaller peatlands or areas with complex geomorphology and limited sampling, measured thicknesses often exceeded contour predictions because interpolation smooths localised peaks and depressions. Despite these limitations, comparison between model-predicted and measured values produced an R^2 of 0.85. This performance is within the range reported by Adetsu et al. (2024), who present R^2 values from 0.23 to 0.89 across multiple sub-models, and exceeds the range reported by Widyastuti et al. (2025) (R^2 = 0.21–0.61). It should be noted, however, that these studies used different methodological approaches, including sensor-based techniques and digital soil mapping, which limits direct comparisons between models. The contour model should therefore be viewed as a robust tool for representing broad spatial patterns in peat thickness and estimating peat volumes, while recognising that localised peat thickness extremes may not always be fully captured.

4.2.2.2 Other mapping techniques

Across the literature, peat thickness has been derived using a spectrum of approaches ranging from direct measurement to spatial modelling. Several studies quantify peat thickness using direct geophysical methods, most notably airborne electromagnetic (AEM) surveying, which determines both the peat surface and subsurface mineral interface to produce three-dimensional peat thickness models without the use of spatial interpolation (Silvestri et al. 2019). Other studies estimate peat depth using regression-based models calibrated with field measurements, where airborne or proximal geophysical data (e.g. gamma ray spectrometry, LiDAR terrain metrics, or electromagnetic sensing) are used as predictors rather than direct measurements (Gatis et al. 2019; Beucher et al. 2020; Koganti et al. 2023). A substantial body of work applies spatial statistical and geostatistical approaches, including inverse distance weighting, ordinary kriging, regression-kriging, empirical Bayesian kriging regression, and related digital soil mapping frameworks, to interpolate peat thickness from field observations (Parry et al. 2012; Munyati and Sinthumule 2021; Henrion et al. 2024; Armanto et al. 2025; Pohjankukka et al. 2025; Widyastuti et al. 2025).

At broader scales, peat thickness has been estimated using empirical models that combine field measurements with environmental variables, but do not use geostatistical methods (Munyati and Sinthumule 2021). Some studies apply machine learning approaches to predict peat thickness from environmental variables, although results are dependent on the quality and representativeness of input data (Li et al. 2024). In contrast, some papers such as the Peat-DBase compilation document measured peat thickness data without modelling (Skye et al. 2025), while comparative review studies synthesise and evaluate existing mapping methods without generating new peat thickness estimates (Minasny et al. 2024).

Comparing studies highlights the importance of method selection based on data density and landscape scale and complexity. Integrating surface elevation with thickness models is increasingly recognised as an effective way to monitor peatland dynamics over time (Cobb et al. 2024; Seidel et al. 2025). However, much like the kriging model used to create our contour maps, other studies in the literature show their models also consistently underestimate peat thickness e.g., Adetsu et al. (2024). Therefore, using data from different sources could improve peat thickness mapping and model accuracy, as they provide information on different aspects of peatland structure and function (Li et al. 2024; Minasny et al. 2024).

4.2.2.3 Recommendations for mapping models and methods

Improving peat thickness modelling and mapping requires more data and refined methods. Increasing sampling density will reduce interpolation uncertainty and improve contour accuracy, particularly in underrepresented bogs and along boundaries. However, future mapping can rely on surface elevation data collected during this survey to replicate and interpolate peat thickness estimates and track subsidence trends, minimizing the need for intensive probing. Further comparative analysis of interpolation techniques such as kriging versus IDW should be undertaken to refine modelling approaches (Munyati and Sinthumule 2021; Armanto et al. 2025), alongside evaluation of surface elevation-based predictions for long-term monitoring. Refinements to peat/Organic Soil boundary delineation is also recommended to avoid model extrapolation into non-peat areas. Together, these steps will support more efficient, accurate peatland monitoring.

4.3 Future peat resource inventory work

Future work should focus on filling in the gaps of spatial coverage to improve the completeness and reliability of peat thickness data. This would involve collecting additional measurements in bogs where existing data are sparse to strengthen models and reduce uncertainty. More strategically distributed and higher density sampling will provide more accurate and representative peat thickness data.

Applying additional methods to better characterise the peat resource is recommended. High-resolution techniques such as LiDAR and ground penetrating radar (GPR) can improve detection of surface elevation, subsurface structure, and the peat–mineral interface, while InSAR is better suited to detecting changes in surface elevation over time. Combining these approaches with ground-based measurements will enhance the consistency and resolution of future inventories.

The definition and identification of peatland boundaries is a key area for improvement, as this is currently a significant source of uncertainty. Future work should prioritise the development of improved boundary delineation methods, combining remote sensing, field validation, and geomorphological or hydrological indicators with existing soil mapping and terrain datasets to better distinguish Organic Soils from adjacent mineral soils (e.g., LiDAR, WoSiS) (Skye et al. 2025; Widyastuti et al. 2025).

5 Conclusion

This study presents an updated assessment of peat thickness across major peat bogs in the Waikato region, integrating new field measurements, historic data, and new geospatial modelling. The use of geostatistical interpolation (kriging) has enabled this work to improve the spatial resolution and reliability of peat thickness information compared with previous surveys, across a wide spatial area. The resulting peat thickness contours provide an estimate of the remaining peat resource within each bog and peatland system. Validation against measured peat thickness and surface elevation data demonstrates strong agreement between measured values and model predictions, which supports confidence in the modelled spatial patterns. While there is some uncertainty around boundary delineation and due to local-scale variability, these limitations are transparently addressed and do not materially affect results at the peatland scale. Overall, this work establishes reproducible methods for peat thickness mapping and surface elevation measurement, demonstrates their suitability for future peatland surveys and monitoring, and adds valuable information to support peatland management, resource assessment, and planning in the Waikato region.

6 References

Adetsu, D.V., Koganti, T., Petersen, R.J., Pedersen, J.B., Zak, D., Greve, M.H. and Beucher, A., 2024. Sensor-based peat thickness mapping of a cultivated bog in Denmark. *Geoderma*, *452*, p.117091.

Armanto, M.E., Zuhdi, M., Setiabudidaya, D., Ngudiantoro, N. and Wildayana, E., 2025. Using the kriging method to establish a spatially reliable interpolator for peat depth variability. *Jurnal Lahan Suboptimal: Journal of Suboptimal Lands*, *14*(1), pp.1-9.

AsureQuality Ltd., 2022. *AgriBase®: National rural property and farm location database for New Zealand*. https://www.asurequality.com/services/other-services/agribase/ [Accessed 1 December 2022].

Belyea, L.R. and Baird, A.J., 2006. Beyond "the limits to peat bog growth": Cross-scale feedback in peatland development. *Ecological Monographs*, *76*(3), pp.299-322.

Beucher, A., Koganti, T., Iversen, B.V. and Greve, M.H., 2020. Mapping of peat thickness using a multi-receiver electromagnetic induction instrument. *Remote Sensing*, *12*(15), p.2458.

Clymo, R.S., 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, *303*(1117), pp.605-654.

Cobb, A.R., Dommain, R., Yeap, K., Hannan, C., Dadap, N.C., Bookhagen, B., Glaser, P.H. and Harvey, C.F., 2024. A unified explanation for the morphology of raised peatlands. *Nature*, *625*(7993), pp.79-84.

Comas, X., Terry, N., Slater, L., Warren, M., Kolka, R., Kristiyono, A., Sudiana, N., Nurjaman, D. and Darusman, T., 2015. Imaging tropical peatlands in Indonesia using ground-penetrating radar (GPR) and electrical resistivity imaging (ERI): implications for carbon stock estimates and peat soil characterization. *Biogeosciences*, *12*(10), pp.2995-3007.

Cooper, M., 2008. *New Zealand North Island Iron Sands Project: Data Processing and Target Generation of Aeromagnetic Survey Data*. SinoSteel Australia Pty Ltd. Report no. RP-080728-01. Ministry of Economic Development New Zealand Unpublished Mineral Report MR4482.

Davoren, A., 1978. *A Survey of New Zealand Peat Resources*. Water & Soil Technical Publication no. 14. Hamilton: The University of Waikato for the National Water and Soil Conservation Organisation. https://webstatic.niwa.co.nz/library/wstp14.pdf

Denyer, K. and Robertson, H., 2016. *National Guidelines for the Assessment of Potential Ramsar Wetlands in New Zealand*. Wellington: Department of Conservation.

Department of Conservation, 2025. *Signs of hope as Whangamarino Wetlands bounces back from fire*. https://www.doc.govt.nz/news/media-releases/2025-media-releases/signs-of-hope-as-whangamarino-wetlands-bounces-back-from-fire/ [Accessed 21 Dec 2025].

Evans, C.D., Irawan, D., Suardiwerianto, Y., Kurnianto, S., Deshmukh, C., Asyhari, A., Page, S., Astiani, D., Agus, F., Sabiham, S. and Laurén, A., 2022. Long-term trajectory and temporal dynamics of tropical peat subsidence in relation to plantation management and climate. *Geoderma*, *428*, p.116100.

Fitzgerald, N., McLeod, M., 2005. *Subsidence rates of peat since 1924 in the Rukuhia swamp*. Environment Waikato Technical Report 2004/20. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr200420/

Gatis, N., Luscombe, D.J., Carless, D., Parry, L.E., Fyfe, R.M., Harrod, T.R., Brazier, R.E. and Anderson, K., 2019. Mapping upland peat depth using airborne radiometric and lidar survey data. *Geoderma*, *335*, pp.78-87.

Glaser, P.H., Janssens, J.A. and Siegel, D.I., 1990. The response of vegetation to chemical and hydrological gradients in the Lost River peatland, northern Minnesota. *The Journal of Ecology*, pp.1021-1048.

Goodrich, J.P., Campbell, D.I. and Schipper, L.A., 2017. Southern Hemisphere bog persists as a strong carbon sink during droughts. *Biogeosciences*, *14*(20), pp.4563-4576.

Goodrich, J.P., Pronger, J., Campbell, D.I., Glover-Clark, G.L., Price, R., Mudge, P., Wyatt, J., Robertson, H., Wall, A.M., Wheatley-Wilson, A. and Schipper, L.A., 2025. Large greenhouse gas emissions from drained peatlands in New Zealand, and the climate mitigation potential of rewetting. *Mires and Peat*, *32*, p.29.

Harvey, M. and Rissmann, C., 2026. InSAR Maps Peatlands in the Waikato Region of New Zealand. *New Zealand Journal of Geology and Geophysics*, *69*(1), p.e70010.

Henrion, M., Li, Y., Koganti, T., Bechtold, M., Jonard, F., Opfergelt, S., Vanacker, V., Van Oost, K. and Lambot, S., 2024. Mapping and monitoring peatlands in the Belgian Hautes Fagnes: Insights from Ground-penetrating radar and Electromagnetic induction characterization. *Geoderma Regional*, *37*, p.e00795.

Hewitt, A.E., 2010. *New Zealand Soil Classification*. 3rd ed. Lincoln: Manaaki Whenua Press. https://cdm20022.contentdm.oclc.org/digital/collection/p20022coll1/id/268/

Hill, R., Borman, D. and Singleton, P., 2020. *Hawke's Bay Peatland Survey 2018*. Hawkes Bay Regional Council Publication No. 5356. Napier: Hawke's Bay Regional Council.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T., 2014. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Switzerland: IPCC.

Johnson, P. and Gerbeaux, P., 2004. *Wetland Types in New Zealand*. Wellington: Department of Conservation.

Koganti, T., Adetsu, D.V., Triantafilis, J., Greve, M.H. and Beucher, A.M., 2023. Mapping peat depth using a portable gamma-ray sensor and terrain attributes. *Geoderma*, *439*, p.116672.

Lambie, S.M. and Ratcliffe, J., 2020. Multi-substrate induced respiration (functional capacity) in agriculturally degraded and intact restiad bogs: implications for carbon and nitrogen cycling. *Mires and Peat*, *26*, p.21.

Li, Y., Henrion, M., Moore, A., Lambot, S., Opfergelt, S., Vanacker, V., Jonard, F. and Van Oost, K., 2024. Factors controlling peat soil thickness and carbon storage in temperate peatlands based on UAV high-resolution remote sensing. *Geoderma*, *449*, p.117009.

Lowe, D.J., 2010. Introduction to the landscapes and soils of the Hamilton Basin. In: D.J. Lowe, V.E. Neall, M. Hedley, B. Clothier and A. Mackay, eds. *Guidebook for pre-conference North Island New Zealand "Volcanoes to ocean", 26th–30th July 2010, 19th World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia, 1–6 August 2010*. Palmerston North: New Zealand Society of Soil Science, pp.1.14–1.61.

Maggs, G.R., 1997. Hydrology of the Kopouatai peat dome. *Journal of Hydrology (New Zealand)*, pp.147-172.

Manaaki Whenua – Landcare Research, 2022. *S-Map Online*. https://smap.landcareresearch.co.nz/

McGlone, M.S., 2009. Postglacial history of New Zealand wetlands and implications for their conservation. *New Zealand Journal of Ecology*, pp.1-23.

McKenzie, S., McLeod, M., 2004. *Subsidence rates of peat since 1925 in the Moanatuatua swamp area*. Environment Waikato Technical Report 2004/17. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr200417/

McLeod, M., Taylor, A., Duncan, L., 2003. *Subsidence rates of peat since 1923 in the Hauraki Plains area*. Environment Waikato Technical Report 2004/18. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr200418/

Milne, J.D.G., Clayden, B., Singleton, P.L. and Wilson, A.D., 1995. *Soil description handbook*. Revised ed. Lincoln: Manaaki Whenua Press. https://doi.org/10.7931/DL1JG6

Minasny, B., Adetsu, D.V., Aitkenhead, M., Artz, R.R., Baggaley, N., Barthelmes, A., Beucher, A., Caron, J., Conchedda, G., Connolly, J. and Deragon, R., 2024. Mapping and monitoring peatland conditions from global to field scale. *Biogeochemistry*, *167*(4), pp.383-425.

Monteverde, S., Healy, M.G., O'Leary, D., Daly, E. and Callery, O., 2022. Management and rehabilitation of peatlands: The role of water chemistry, hydrology, policy, and emerging monitoring methods to ensure informed decision making. *Ecological Informatics*, *69*, p.101638.

Munyati, C. and Sinthumule, N.I., 2021. Comparative suitability of ordinary kriging and Inverse Distance Weighted interpolation for indicating intactness gradients on threatened savannah woodland and forest stands. *Environmental and Sustainability Indicators*, *12*, p.100151.

Naish, T. R., 1990. *Late Holocene mud sedimentation and diagenesis in the Firth of Thames: Bentonites in the making*. Thesis, Master of Science (MSc): University of Waikato. https://hdl.handle.net/10289/7988

Navarro, Y.H., Moreira-Turcq, P., Espinoza, R., Llanos, R., Apaéstegui, J., Turcq, B. and Willems, B., 2020. Influence Of Climate Changes on Carbon Accumulation in High Andean Peatlands During the Last 2 500 Years. *Ecología Aplicada*, *19*(1), pp.35-41.

O'Leary, D., Brown, C., Hodgson, J., Connolly, J., Gilet, L., Tuohy, P., Fenton, O. and Daly, E., 2025. Airborne radiometric data for digital soil mapping of peat at broad and local scales. *Geoderma*, *453*, p.117129.

Palmer D, Hainsworth S. 2012. *Lower Waikato Catchment Peatland Survey*. Landcare Research Contract Report LC1122. Hamilton: Waikato Regional Council. Doc ID 2278192.

Parry, L.E., Charman, D.J. and Noades, J.P.W., 2012. A method for modelling peat depth in blanket peatlands. *Soil Use and Management*, *28*(4), pp.614-624.

Parry, L.E., West, L.J., Holden, J. and Chapman, P.J., 2014. Evaluating approaches for estimating peat depth. *Journal of Geophysical Research: Biogeosciences*, *119*(4), pp.567-576.

Pawson, E. and Brooking, T., 2013. *Making a new land: environmental histories of New Zealand*. New ed. Dunedin: Otago University Press.

Pohjankukka, J., Räsänen, T.A., Pitkänen, T.P., Kivimäki, A., Mäkinen, V., Väänänen, T., Lerssi, J., Salmivaara, A. and Middleton, M., 2025. Digital mapping of peat thickness and extent in Finland using remote sensing and machine learning. *Geoderma*, *455*, p.117216.

Pribyl, D.W., 2010. A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, *156*(3-4), pp.75-83.

Pronger, J., 2013. *Historic and contemporary subsidence rates of drained agricultural peat, Waikato, New Zealand*. Unpublished BSc (Hons) dissertation: University of Waikato.

Pronger, J., Glover-Clark, G., Mudge, P., Brasington, J., Wyatt, J., Schipper, L., 2021. *Waikato regional peat subsidence LiDAR monitoring*. In press. Waikato Regional Council Technical Report 2022/26. Hamilton: Waikato Regional Council.

Pronger. J., Mudge, P., Brasington, J., Schipper, L., Wyatt, J., 2020. *Development and testing of a method to monitor peatland subsidence in the Waikato Region*. In press. Waikato Regional Council Technical Report 2022/25. Hamilton: Waikato Regional Council.

Pronger, J., Mudge, P., Fraser, S., Brasington, J., Schipper, L., 2019. *Approaches to monitor peatland subsidence in the Waikato Region*. In press. Waikato Regional Council Technical Report 2022/14. Hamilton: Waikato Regional Council.

Pronger, J., Price, R., Mudge, P., Brasington, J., Louis, S. and Wyatt, J., 2021. *Development of a regional peat subsidence monitoring network*. In press. Waikato Regional Council Technical Report 2022/15. Hamilton: Waikato Regional Council.

Pronger, J., Schipper, L.A., Hill, R.B., Campbell, D.I. and McLeod, M., 2014. Subsidence rates of drained agricultural peatlands in New Zealand and the relationship with time since drainage. *Journal of Environmental Quality*, *43*(4), pp.1442-1449.

Pronger, J., Wyatt J. and Glover-Clark, G., 2022. *Review of potential management interventions to reduce peat subsidence and CO2 emissions in the Waikato*. Waikato Regional Council Technical Report 2021/10. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr202110/

Province of British Columbia, 2025. *Lesson 5: Transect Layout & Wetland Classification*. British Columbia, Canada: Ministry of Forests. https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/integrated-resource-monitoring/forest-range-evaluation-program/frep-training/wetland-protocol-self-guided-training/lesson-5-transect-layout-wetland-classification

R Core Team, 2025. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Seidel, R., Dettmann, U. and Tiemeyer, B., 2025. Peatland Surface Motion: Terminology, Measurement Approaches, Models and Insights from a Global Dataset. *Ecohydrology*, *18*(8), p.e70140.

Selby, M.J. and Lowe, D.J., 1992. The middle Waikato Basin and hills. In: J.M. Soons and M.J. Selby, eds. *Landforms of New Zealand*. Auckland: Longman Paul.

Silvestri, S., Knight, R., Viezzoli, A., Richardson, C.J., Anshari, G.Z., Dewar, N., Flanagan, N. and Comas, X., 2019. Quantification of peat thickness and stored carbon at the landscape scale in tropical peatlands: A comparison of airborne geophysics and an empirical topographic method. *Journal of Geophysical Research: Earth Surface*, *124*(12), pp.3107-3123.

Skye, J., Melton, J.R., Goldblatt, C., Saumier, L., Gallego-Sala, A., Garneau, M., Winton, R.S., Bahati, E.B., Benavides, J.C., Fedorchuk, L. and Imani, G., 2025. Peat-DBase v. 1: a compiled database of global peat depth measurements. *Earth System Science Data Discussions*, *2025*, pp.1-26.

Sun, J., Gallego-Sala, A. and Yu, Z., 2023. Topographic and climatic controls of peatland distribution on the Tibetan Plateau. *Scientific Reports*, *13*(1), p.14811.

Te Uru Kahika, n.d. *Wells Database*. https://wellsnz.teurukahika.nz/

Thakur, H., 2015. *Proposed Muggeridges pumpstation - drainage management plan*. Waikato Regional Council Technical Report 2015/18. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr201518/

Wheatley-Wilson, A., Wyatt, J., 2024. *Organic soil greenhouse gas emissions accounting for the Waikato Region*. Waikato Regional Council Technical Report 2023/06. Hamilton: Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr202306/

Widyastuti, M.T., Minasny, B., Padarian, J., Maggi, F., Aitkenhead, M., Beucher, A., Connolly, J., Fiantis, D., Kidd, D., Ma, Y. and Macfarlane, F., 2025. Digital mapping of peat thickness and carbon stock of global peatlands. *Catena*, *258*, p.109243.

Wilkinson, S.L., Tekatch, A.M., Markle, C.E., Moore, P.A. and Waddington, J.M., 2020. Shallow peat is most vulnerable to high peat burn severity during wildfire. *Environmental Research Letters*, *15*(10), p.104032.

7 Appendix A – Peat thickness probing methods – extended field guide

7.1 Standard probing procedure

At each thickness measurement site location, peat thickness was measured at five points (central point plus four points 3 m away in the N,S, E, W directions). The following procedure was used:

1. Surface clod was removed using a spade.
2. At the central point, a small pit was excavated to 60 cm depth to examine peat characteristics (e.g., colour, structure, von Post), and record observations in Field Maps.
3. The peat probe was inserted vertically through the peat.
4. Extension rods of known length were added as required.
5. When the peat base was reached, the length of rod remaining aboveground was measured.
6. Rods were withdrawn and the number and total inserted lengths was recorded.
7. Peat thickness was calculated by subtracting the measured aboveground length from the total inserted length.
8. If the auger tip retrieved mineral material, its thickness was subtracted from the total to avoid overestimating peat thickness.
9. The material immediately beneath the peat base was recorded and photographed.

7.1.1 Field considerations

- Keep the probe perpendicular during insertion to avoid curvature and overestimation.
- If hard layers are encountered above the expected base, attempt to penetrate gently before relocating slightly and re-probing.
- Use the probe extractor where needed and follow safe lifting practices.

7.2 Shallow peat and boundary sites

Near the boundary of the peat resource survey areas, or adjacent to low rolling hills, surveyors will encounter either very shallow peat or mineral soils (non-peat soils) at some of our thickness measurement sites. The peat recorded during the previous survey in 1976 may have gone or reduced due to subsidence processes including shrinkage, consolidation, and oxidation.

For this survey peat is defined as an Organic Soil under the New Zealand Soil Classification (Hewitt 2010). To be an Organic Soil,

- there must be >30 cm of Organic Soil material within 60 cm of the soil surface, and entirely formed from peat or organic material
- the organic soil material must have >18% carbon content.

For all sites where it is anticipated that peat will be <1 m, use a Dutch auger to confirm the presence and thickness of peat at the site.

- Auger down incrementally ensuring that only the length of auger head is sampled each time.

- If organic material or peat is observed record the thickness of the peat.
- If the surveyor is not confident that the observed diagnostic material has >18% carbon content, or it is <30 cm then then it should be sampled.
    - Record the thickness of the material of interest and its depth (the diagnostic layer),
    - Take a photo of the soil profile and include a tape measure for scale, ensuring the diagnostic layer is clearly visible in the photo).
    - Collect about 2 cups of material that represents the diagnostic layer.
    - Place the sampled material into a sample bag, press the air out and seal it.
    - Label the bag with site_date_diagnostic layer thickness (e.g. 457_13/2_0–25 cm).
    - Store the sample bag in a cool, dry place until it is taken to the laboratory for analysis of soil carbon and organic matter. Record that samples have been collected in the field dairy.

Notes

- The base of the peat is typically struck when a grey, blue, green or light brown clayey, silty, or sand material is struck (Figure 41).
- Examples of Organic Soils and soils that do and do not meet the criteria for Organic Soils are shown in Figure 42 and Figure 43, respectively.
- Note that Organic Soil material that is used to diagnose a peat soil is not always “black”. It can be brown.
- If unsure always sample.

Figure 41. Examples of the transition between peat and subsurface material. Note the light-coloured material in the auger tip (left-hand photo) and peat probe tip (middle and right-hand photos), this is not organic material. However, the darker material further up the auger tip could be, perhaps with a relatively low carbon content.

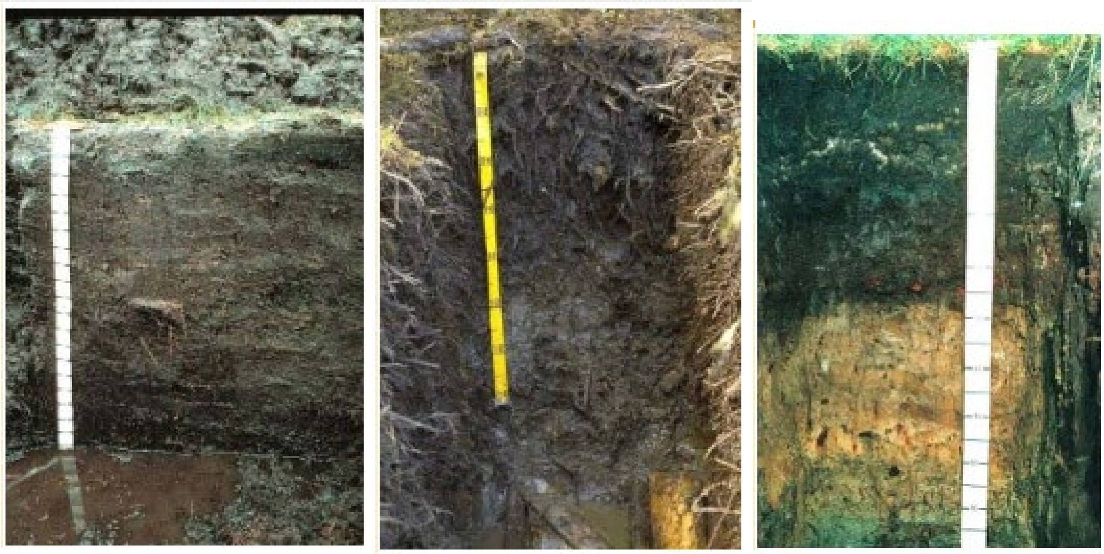


Figure 42. Examples of Organic Soils, note the mineral (non-Organic material) beneath the Organic Soil on the right.

Figure 43. Examples of profiles that don't meet the diagnostic criteria to be an Organic Soil. The soil on left only had 22 cm of Organic Soil material (note the light coloured gleyed material below) the soil on the right is a mineral soil.

7.3 Difficult probing conditions

Common issues with probing include fluid or fine mineral silts adhering to the drill bit and obscuring the transition (e.g., at Huntly) as well as buried wood obstructed probe advancement (e.g., at Rukuhia). Where uncertainty occurred:

- The point was reattempted up to five times within ~1 m radius.
- If unsuccessful, the point was abandoned, and the site thickness was calculated from the remaining successful measurements.

7.4 Recording data

For each probing point, the following information was loaded in Field Maps:

- NZTM location

- Property address and owner details (from WRC spatial layers and AgriBase)
- Current land cover
- Approximate peat thickness in 1976 (derived from PEAT_DEPTH_CONTOURS)

The following information was recorded in Field Maps upon arrival at the site:

- Peat thickness measurements at 5 points (centre, north, south, east, west)
- Notes and photographs of peat characteristics and the base material of the peat
- Any diagnostic samples collected
- Other site-specific information e.g., von Post, water table depth, land use, vegetation, weather conditions

Peat thickness values were later entered into a central spreadsheet, and the mean thickness across the five points at each site was calculated. At each site GPS coordinates were taken in Field Maps to identify sample locations and assist with relocating the sites in the future.

8 Appendix B – Surface elevation measurement instructions – extended field guide

8.1 System setup and network connection

Instructions for setting up the RTK GNSS (Trimble R10/R8 and TSC5) and connecting to the VRS Now network are provided in *Supplementary material S4.*

8.2 Daily reference check

A reference measurement must be taken at a local geodetic marker at the start (and/or end) of each survey day.

1. Connect the RTK GNSS rover to the selected CORs network (VRS Now).
2. Record the geodetic marker elevation using standard RTK GNSS settings
3. Verify that the measured elevation matches the published benchmark within acceptable tolerance (20 mm).

8.3 Surface elevation measurements at field sites

For each manual probing point:

1. Connect to the CORs network (VRS Now).
2. Survey the five 1 m^2 patches per site (25 points per patch; 125 points total).
3. Ensure the survey staff is held perpendicular to the ground using the spirit level bubble.
4. On soft ground, place a small flat foot under the staff tip to prevent penetration into the peat surface.

8.4 Post-survey data handling

Back in the office:

1. Download and process GNSS data following the standard Trimble Access workflow.
2. Save final datasets to the designated project directory.

8.5 Notes on equipment use

- RTK GNSS equipment is sensitive and must be handled with care.
- Ensure clear sky visibility where possible to maintain satellite connection.
- If network corrections drop, pause surveying until the connection is restored.

9 Appendix C – Von Post index

Table 4. Von Post Index describing a 10-point scale of peat humification as an indicator of the degree of decomposition, assessed in field based on physical characteristics e.g., plant structure, soil water colour. Sourced from Province of British Columbia (2025).

<table>
<tr><th colspan="2">VP Classification</th><th>Decomposition</th><th>Plant structures</th><th>Water</th><th>Peat Escape</th></tr>
<tr><td rowspan="3">Fibric Peat</td><td>1</td><td>None</td><td>Unaltered</td><td>Clear or light yellow-brown</td><td rowspan="3">No peat escapes</td></tr>
<tr><td>2</td><td>Almost none</td><td rowspan="3">Distinct</td><td>Light yellow brown</td></tr>
<tr><td>3</td><td>Very weak</td><td>Turbid brown</td></tr>
<tr><td rowspan="3">Mesic Peat</td><td>4</td><td>Weak</td><td>Strongly brown turbid</td><td>Very little peak escapes</td></tr>
<tr><td>5</td><td>Moderate</td><td>Clear but becoming indistinct</td><td>Very strongly brown turbid. Some peat suspension</td><td>Some peat escapes</td></tr>
<tr><td>6</td><td>Moderately strong</td><td>Somewhat indistinct</td><td>Muddy with much suspended peat</td><td>Aprox. ⅓ of peat escapes</td></tr>
<tr><td rowspan="4">Humic Peat</td><td>7</td><td>Strong</td><td>Indistinct but recognizable</td><td>Strongly muddy</td><td>Aprox. ½ of peat escapes</td></tr>
<tr><td>8</td><td>Very Strong. Remnants resistant to decomposition (ex. roots and wood)</td><td>Very indistinct</td><td>Thick mud with little water</td><td>Aprox. ⅔ of peat escapes</td></tr>
<tr><td>9</td><td>Almost complete</td><td>Almost unrecognizable</td><td rowspan="2">No water</td><td>Almost all peat escapes</td></tr>
<tr><td>10</td><td>Complete</td><td>Unrecognizable</td><td>All peat escapes</td></tr>
</table>

10 Appendix D – Supplementary material index

Table 5. Supplementary material index.

Index	Name	Document format	Document info	Accessibility
S1	Peat Thickness Final ALL	Excel spreadsheet	Peat thickness information	Available upon request
S2	Peat surface Elevation Data with 2021 LiDAR DEM	Excel spreadsheet	Measured 2023 peat surface elevation data alongside LiDAR DEM information	Available upon request
S3	R code	R code	R script for creating contours using thickness information	Available upon request
S4	GNSS surveying with Trimble for peat resources survey	Word document	Extended instructions on using the Trimble GNSS surveying gear for measuring surface elevation	Available upon request
S5	Wells data	Excel spreadsheet	Final wells selected for use in thickness data (all wells data can be found at https://wellsnz.teurukahika.nz/	Available upon request

11 Appendix E – Borehole peat thickness data and conditions

11.1 Finalised wells data

See *Supplementary material S5.*

11.2 Inclusion and exclusion criteria for borehole data

Inclusion Criteria

- Intersect Wells Aotearoa Data with Organic Soils boundary.
- Include sites where the major fraction of the surface stratum is peat.
    - If peat exists below surface mineral soil, this will be classified as mineral soil with peaty layer (outside study scope).

Exclusion Criteria

- Remove sites if:
    1. If the surface layer major fraction is not purely classed as *Peat*, i.e., any of the following: *Silt, Sand, Clay, Mud, Overburden, Soil, Peaty Soil, NULL, or Undefined.*
    2. If the secondary fraction is described (e.g., pumice, sand), remove. Anything in secondary fraction indicates a possible misunderstanding of what the layer is e.g., a sandy Peat (major fraction = peat, secondary fraction = sand), possibly the environment was alternating between peat growth and flooding of river overbank.
    3. If the surface layer is <0.3 m, treat as mineral soil with peaty layer, remove.
    4. If no drilling date exists, the subsidence cannot be calculated, so the well must be deleted from the dataset.
    5. If the location is in a town or lake (these types of sites were not measured in this survey, and we don't know anything about them).
    6. If an uninterrupted peat layer exceeds 18 m, remove. It is unlikely to find an uninterrupted, homogenous layer of surface peat of this thickness. Most peatlands formed in New Zealand after the last glaciation 18,000 years ago (McGlone 2009) and mapped against known peat accumulation rates 1 mm a year (Goodrich et al. 2017), this equates to 18 m of peat accumulation in this time.
    7. If the thickness is unreasonably high in context of other sites e.g., if the well depth is more than 3 standard deviations from the mean of the 2023 survey results for each bog (Table 6).

Additional notes

- Subsidence rate adjusted per bog using Pronger et al. (2014).
- Wells located >2 km outside peat boundaries were considered but excluded due to unaccounted small peat pockets that are out of the scope of this study.
- For wells detected within the Organic Soils boundary that were keyed out as non-OS, these were totally excluded from the dataset, rather than assigning the peat as <0.3 m. This is

because field classification of peat is subjective and we don't know the methods used for determination.

Table 6. Mean and standard deviation of 2023 peat thickness measurements, with the upper exclusion threshold (mean + 3 SD) applied to identify exceptionally deep sites.

Bog	Mean	SD	Upper Threshold
Hauraki	1.77	1.35	5.80
Hauraki East	3.11	0.36	4.17
Hoe o Tainui	5.06	3.15	14.50
Kainui	2.14	1.77	7.46
Komakorau	1.76	1.39	5.94
Kopuatai	2.74	2.27	9.55
Moanatuatua	2.84	2.26	9.62
Ohinewai	7.69	1.57	12.40
Ohote	1.57	1.10	4.87
Orini	5.03	2.02	11.08
Rukuhia	5.64	2.33	12.62
Te Mimiha	7.27	3.47	17.67
Whangamarino	0.15	0.14	0.57

* Threshold values were calculated using unrounded mean and standard deviation values; therefore, calculations based on the rounded values presented in this table may differ slightly due to rounding.

12 Appendix F – Boundary methods extended

This appendix provides the detailed decision rules, GIS procedures, and exceptions used to refine Organic Soil boundaries. This section expands on section 2.5.1 by reiterating the importance of boundaries in constraining contours, documenting the operational workflow required for reproducibility, including the inclusion/exclusion rules for thickness sites, the decision logic for selecting between boundaries, or using buffers, the GIS steps used to prepare and select line segments, the handling of edge cases and topographic or structural constraints, and notes on confidence, assumptions, and rationale.

12.1 Importance of the boundary in constraining contours

A well-defined boundary is essential for constraining interpolation and contouring to the true extent of the peat deposit. It prevents unrealistic extrapolation, preserves the natural geometry of the landform, reduces edge effects in interpolation, and ensures that contours represent meaningful patterns within the bog. A robust boundary also supports accurate area and volume calculations and clearer, more defensible maps for management and planning purposes. See Figure 44 below of an early-stage example of unconstrained peat thickness contouring where the peat contours extend beyond the unmapped boundary of the bog.

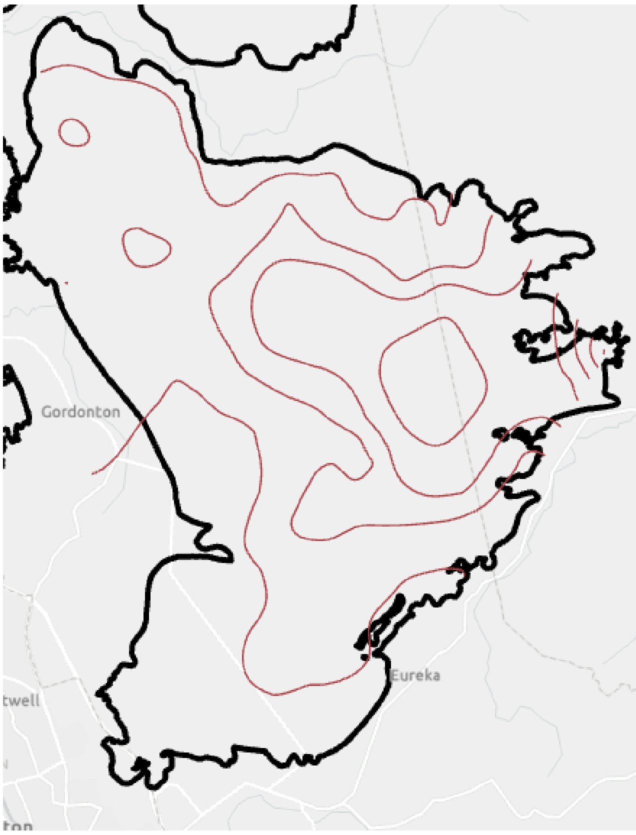


Figure 44. Early-stage contours for Komakorau showing the importance of a good boundary for constraining the contour lines within the known extent of Organic Soils.

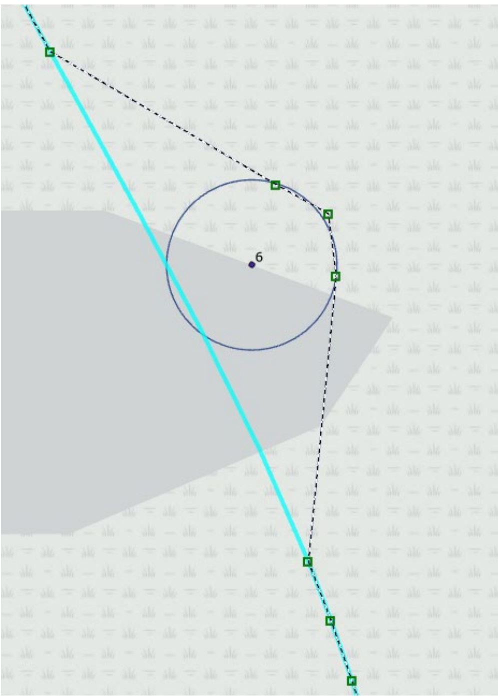
12.2 Decision process

1. S-Map is the primary boundary source and is used as the default boundary.
2. When peat thickness of a measured site is >0.3 m and is located outside of the S-Map boundary – refer to 12.2.1.

3. When peat thickness of a measured site is <0.3 m and is located inside the S-Map boundary – refer to 12.2.2.
4. When there are both <0.3 m and >0.3 m measured peat thickness sites within the same area and they need differentiating – refer to 12.2.3.

12.2.1 Sites outside the S-Map boundary (>0.3 m)

1. If FSL or Davoren boundaries enclose the >0.3 m site, select between them based on topography (remove the site if it is located on a distinct slope or hill edge), surrounding thickness values (enclose site only if consistent with adjacent thickness measurements), and the smallest polygon closest to the S-Map boundary.
2. When S-Map, FSL, and Davoren all fail to sensibly enclose the >0.3 m site, the site will need to be included using an outward buffer to the nearest adopted boundary (not necessarily the original S-Map boundary) by following these rules (Figure 45):



a. Apply a circular buffer around the site and expand until the buffer intersects the S-Map boundary (or nearest new boundary created in steps A. and B.)

b. Shift the vertices of the existing boundary line so they encompass the buffered circle around the site.

c. Truncate buffers where blocked by rivers, waterbodies, steep slopes (from LiDAR DEM), and anthropogenic exclusions (quarries, stop banks, infrastructure).

Figure 45. Example of a >0.3 m site located outside of the original location of the boundary (light blue line) where the buffering inclusion method is required to enclose the site within the area of Organic Soil. The line (blue dashed) can be shifted using vertices (green squares) along the line.

12.2.2 Sites inside the S-Map boundary (<0.3 m)

1. As above, select the nearest FSL or Davoren line that plausibly represents a peat boundary, and excludes the <0.3 m site without producing unrealistic boundary geometry. See Figure 46 below illustrating a scenario where a measured site of <0.3 m is located within the S-Map boundary but can be excluded using the Davoren and FSL lines.

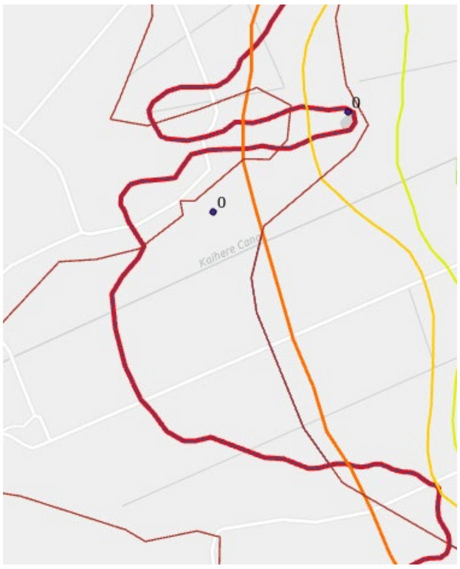


Figure 46. Example of S-Map (red), FSL (brown), and outer Davoren (orange) boundary lines near a <0.3 m measured site that needs to be excluded from within the inner side (to the right in this image) of the S-Map polygon. In this case, the Davoren, FSL, or both lines can be used.

2. If <0.3 m site is inside of S-Map boundary and there is no other sensible boundary to exclude it, the site will need to be excluded using an inward buffer to the nearest adopted boundary:
    a. Follow the rules in section 12.2.1, step 2. a – c in reverse to buffer the site out of the Organic Soils polygon.
3. Ensure the new lines created in both this section and section 12.2.1 do not include/exclude adjacent <0.3 m/>0.3 m sites into/out of the existing Organic Soils boundary. If this is going to occur, refer to section 12.2.3 below.

12.2.3 Sites <0.3 m and >0.3 m within the same area

1. If >0.3 m and <0.3 m sites co-occur on the same side of a boundary and no separating historic line exists, use a combination of S-Map, FSL, & Davoren boundaries, DEM guidance, and limited buffering.
2. Where buffering is the most suitable option, follow these steps:
    a. Locate the <0.3 m site closest to the boundary before dealing with sites closer to the centre of the bog.
    b. Add a buffer around this site until the circle intersects with the existing boundary.
    c. Where there is another <0.3 m site between the <0.3 m site of interest and the boundary – use the nearest <0.3 m site buffer circle as the boundary and buffer to this line (as in step b.)
    d. Where there is no nearby boundary line and no nearby buffered circle, this could mean that if the site is buffered to intersect with the nearest circle/boundary, it ends up engulfing a nearby >0.3 m site. To avoid this, we must subtract the <0.3 m site thickness (e.g., 0.15 m) from 0.3 m (e.g., 0.3–0.15 = 0.15 m). (Note: 0.3 m is the lowest S-Map value so this is what we will use for the buffer boundary in this case).
    e. Find the nearest >0.3 m site in any direction and subtract the value from Step 4 (0.15 m) from this site (e.g., nearest site thickness = 1.8 m - 0.15 m = 1.65 m)
    f. Take the result from Step e. and work out the percentage of the thickness in relation to the nearest site e.g., (1.65/1.8) x 100 = 92%

g. Measure the distance between the <0.3 m site and the nearest >0.3 m site e.g., distance between 1.8 m site and the <0.3 m site = 220 m.
h. Use the percentage calculated in Step f. and multiply this by the distance measured in Step g (e.g., 92% of 220 m = 202 m)
i. Calculate the difference between the total distance between sites (Step g.) and the calculated percentage of this difference (Step h.) (e.g., 220 - 202 = 18 m).
j. Measure the remaining distance from Step i. (e.g., 18 m) from the <0.3 m site (0.15 m thickness site) and apply this to the buffer distance.

Overall, the final choice is made via informed subjectivity, prioritising grouping of sites, plausible geomorphology, segment-by-segment consistency, and avoidance of excessive “bites” into the boundary.

12.3 Line segmentation in GIS

To enable selective retention or deletion of individual line segments, all boundary layers (S-Map, FSL, Davoren) were converted into a common editable format.

1. All historical and contemporary boundaries were combined into a single multi-line layer.
2. Run the *Intersect* tool on the merged layer to identify all sites where lines cross or touch. These intersection sites define where lines can later be split.
3. To produce small, individually selectable line segments, use *Split Line at Point* with:
    - Input features = merged boundaries
    - Point features = intersection points
    - Search radius = 100 m
4. Segments were manually kept or removed based on the rules in section 12.2.

12.4 Guiding Principles

When multiple historic boundary layers are available (FSL and Davoren), the smallest and most conservative polygon that encloses the relevant thickness site(s) is selected. Boundaries are not extended into topographically implausible areas such as slopes, ridgelines, or cut banks, nor into areas known to be non-peat based on aerial imagery, LiDAR, existing mapped boundaries such as S-Map, or field observations. Streams and waterbodies are treated as firm peat boundaries because active channels do not support peat accumulation. Buffering is applied only where mapped boundaries are unsuitable or absent. Confidence in each chosen boundary segment is assessed qualitatively, and all decisions are informed by local topography, the proximity and pattern of neighbouring thickness sites, soil group classifications in the FSL, LiDAR-derived DEMs, and the presence of rivers, streams, drains, quarries, or urban areas. Although inherently subjective, this assessment provides transparency in areas where boundary certainty is low (as marked by the hashed areas in the contour maps of the results section).

Handling Special Geographic Cases

Streams and waterbodies

- Treated as hard peat boundaries.
- Bog extents were split where streams bisected peatlands (e.g., Hauraki/Kopuatai).

Multiple bog units under the same name

Where separate geomorphic units exist (e.g., divided by rivers or hills), boundaries were kept separated to prevent kriging from “bridging” units.

Small bogs with limited sites

Where data is sparse, the S-Map boundary is retained by default unless contradicted by high-confidence thickness measurements.

12.5 Completion

Once the final boundary was selected for a bog:

1. The line was checked against DEM, imagery, and adjacent sites.
2. The finalised polyline was converted into sites at 200 m spacing.
3. Sites were exported as a CSV representing 0.3 m thickness constraints for kriging.

13 Appendix G – Statistical R and ArcGIS methods for creating contours

13.1 Kriging methods (description of R script)

Step 1. Load and prepare data

Peat thickness survey data were imported from CSV files containing spatial coordinates and thickness measurements.

Step 2. Create grid covering area of bog

A convex hull was generated around the thickness measurement sites to define the spatial extent of the bog. A 25 m buffer was applied to the hull, and a regular grid with 25 m resolution was created within this buffered area.

Step 3. Trend Surface Modelling

Two types of trend surfaces were fitted to the peat thickness data:

- **Quadratic Regression Model**: A second-order polynomial surface was fitted using the R lm() function, incorporating linear, squared, and interaction terms of easting and northing.
- **Thin-Plate Spline Model**: A smooth surface was fitted using the R gam() function from the mgcv package.

Model residuals were assessed for normality using Q-Q plots, histograms, and the Shapiro-Wilk test[22].

4. Residual Kriging

Ordinary kriging was applied to the residuals of both models using the R gstat package:

- Empirical variograms were computed and fitted with spherical models using the variogram() function.
- Kriging was performed over the grid to interpolate residuals using the krige() function.
- Cross-validation (Leave-One-Out)[23] was conducted to assess model performance, and RMSE[24] was calculated.

5. Combined Prediction Surfaces

Predicted trend surfaces were combined with kriged residuals to produce final spatial prediction surfaces for peat thickness. These surfaces were visualised using R ggplot2 with viridis color scales.

6. Exporting Results

[22] The Shapiro–Wilk test assesses whether a dataset follows a normal distribution. The test is applied to model residuals (observed minus predicted values) to assess whether they are approximately normally distributed. A non-significant (p >0.05) suggests the residuals do not differ significantly from a normal distribution.

[23] Leave-one-out cross-validation tests how well the kriging model predicts known peat thickness measurements when those measurements are treated as unknown. Lower prediction errors indicate a more reliable interpolation model.

[24] RMSE measures how accurately the interpolation model predicts peat thickness at unsampled locations. Lower RMSE values indicate that predicted peat thickness values are closer to measured values.

Final prediction surfaces were exported as:

- CSV files for use in GIS platforms.
- GeoTIFF raster files using the raster package, with NZTM2000 projection for compatibility with New Zealand geospatial datasets.

13.2 R script for generating contours

See *Supplementary material S1*.

13.3 Model considerations

13.3.1 Choosing the best variogram model

Choosing the correct variogram model is important in kriging because it directly affects the accuracy and reliability of spatial predictions. The variogram defines how spatial correlation between data sites changes with distance, and this influences the weights assigned to neighbouring observations during interpolation. If the model poorly represents the true spatial structure, for example, by underestimating or overestimating the range or sill, it can lead to biased predictions, over-smoothing, or exaggerated variability. Kriging also predicts values as well as estimates uncertainty, and a misfit variogram can distort these confidence intervals. In short, a well-chosen variogram ensures that kriging captures the spatial patterns realistically, leading to more reliable and interpretable results.

1. **Plot the Empirical Variogram**
    - Calculate the experimental (empirical) variogram from your data to show how semivariance changes with distance.
2. **Fit Candidate Models**
    - Fit several theoretical models (e.g., spherical, exponential, Gaussian) to the empirical variogram.
    - Use least squares or maximum likelihood methods to estimate parameters like nugget, sill, and range.
3. **Assess Goodness of Fit**
    - Compare how well each model fits the empirical variogram visually and statistically.
    - Use metrics like residual sum of squares (RSS) or cross-validation error.
4. **Cross-Validation**
    - Perform kriging using each model and compare prediction accuracy.
    - Use techniques like leave-one-out cross-validation to evaluate prediction error (e.g., RMSE, MAE).
5. **Consider Spatial Characteristics**
    - Choose a model that reflects the nature of your data:
        - **Spherical**: good for moderate spatial correlation.
        - **Exponential**: suitable for short-range correlation.
        - **Gaussian**: best for smooth, continuous data.
        - **Power or linear**: for non-stationary or trending data.

Each model has a different shape and behaviour, and the choice depends on the spatial characteristics of your data. The best variogram model is the one that fits your empirical data well, minimises prediction error, and reflects the spatial structure of your dataset.

The Spherical ("Sph") variogram model was the best fit according to RMSE results (lowest value is best). Exponential and Pentaspherical were other models that fit well for a number of bogs, but spherical was the best model overall across all bogs. Logarithmic, power, periodic and at times linear models did not generate a result (NaN RSME produced). Matsens and Stein models produced the same RMSE as the Exponential model so were excluded in favour of the Exponential model. When the higher-ranked variogram models (based on low RMSE) were compared visually (by observing the contours produced in ArcGIS Pro by the raster grid generated in R), the results were identical. Lower ranked models were not visualised. Table 7 summarises the kriging model settings chosen for this data.

Table 7. Summary of kriging model settings used for peat thickness contour generation in R.

Parameter	Setting used
Spatial modelling approach	Regression kriging (trend surface modelling followed by ordinary kriging of residuals)
Trend surface model	Thin-plate spline fitted using the gam() function in the mgcv package
Alternative model evaluated	Quadratic regression surface
Variogram model	Spherical
Variogram fitting	Empirical variogram fitted using the variogram() function in gstat
Kriging method	Ordinary kriging applied to spline residuals (regression kriging workflow)
Model selection criteria	Leave-one-out cross-validation, RMSE, variogram characteristics, Durbin–Watson statistic[25], and Akaike Information Criterion (AIC)[26]
Prediction grid resolution	25 m (50 m for Komakorau).
Prediction extent	Convex hull of measurement sites with a 25 m buffer
Boundary constraints	Organic Soil boundaries converted to 0.3 m peat thickness points at 200 m intervals
Coordinate system	NZTM2000
Outputs	GeoTIFF raster and CSV

13.3.2 Spline versus quadratic models

The R script for creating contours (*Supplementary material S3*) uses a number of statistical techniques to compare the spline and quadratic models including RMSE, Durban-Watson tests, and an AIC comparison. These tests can generate results for each bog to test the fitness of the

[25] The Durbin–Watson test is used to assess whether residuals from the trend surface models still contained spatial structure. Strong autocorrelation suggests the trend model has not fully explained the spatial pattern and that additional structure remains for the kriging stage to model. Values near 2 indicate little autocorrelation. Values substantially less than 2 indicate positive autocorrelation, while values greater than 2 indicate negative autocorrelation.

[26] AIC was used to compare the alternative trend surface models (e.g., spline versus quadratic). Models with lower AIC values provide a better balance between explaining the data and avoiding unnecessary complexity.

models. The variogram for the quadratic model residuals generally showed a higher sill and longer range, indicating greater residual variability and spatial correlation over a wider area. In contrast, the spline model residuals have a much lower sill and a shorter range, suggesting that the spline model captures more spatial structure, leaving less residual variation. Overall, the spline model provides a better fit to the spatial pattern, reducing the need for kriging adjustments.

The cross-validated RMSE for the quadratic model and the spline model came back almost identical for all bogs, indicating that both models have similar predictive accuracy when evaluated through leave-one-out cross-validation. Despite this similarity in RMSE, the spline model is still preferable because it shows lower residual spatial variability (variogram), reduced autocorrelation (Durbin–Watson), and a much better AIC score, meaning it provides a more robust representation of spatial structure.

The Durbin–Watson tests indicate strong positive autocorrelation in residuals for both spline and quadratic models, but the effect was generally more pronounced in the quadratic model compared to the spline model (DW closer to 2). A DW value close to 2 suggests no autocorrelation, so these results confirm that the quadratic model leaves substantial spatial structure unaccounted for, while the spline model reduces autocorrelation considerably, providing a better representation of spatial dependence. An example of analysis for Rukuhia is shown below:

- **RMSE**: The variogram for the quadratic model residuals shows a higher sill (around 6.5) and a longer range (~2,500 m), indicating greater residual variability and spatial correlation over a wider area. In contrast, the spline model residuals have a much lower sill (around 2.5) and a shorter range (~1,500 m), suggesting that the spline model captures more spatial structure, leaving less residual variation. Overall, the spline model provides a better fit to the spatial pattern, reducing the need for kriging adjustments.
- **Durban Watson tests**: The Durbin–Watson tests indicate strong positive autocorrelation in residuals for both models, but the effect is much more pronounced in the quadratic model (DW = 0.13) compared to the spline model (DW = 0.92). A DW value close to 2 suggests no autocorrelation, so these results confirm that the quadratic model leaves substantial spatial structure unaccounted for, while the spline model reduces autocorrelation considerably, providing a better representation of spatial dependence.
- **AIC comparison:** The AIC comparison strongly favours the spline model (AIC = 2870.4) over the quadratic model (AIC = 3534.2), indicating that the spline provides a substantially better fit to the data. Combined with the lower residual variability and reduced autocorrelation observed in the variogram and Durbin–Watson tests, this suggests that the spline model captures the spatial structure more effectively than the quadratic trend surface.

13.3.3 Cell size and other boundary considerations

When creating the grid to cover the bog area, you must select a cell size to determine how granular you want the data to be. The grid cell size controls the resolution of the prediction surface and contour display rather than the spatial resolution supported by the underlying peat thickness measurements. The effective resolution of the contours is constrained by the density and distribution of measurement sites. We found a cell size of 25 m produced the most granular lines without losing the ability for R to successfully run for all bogs, apart from Komakorau which required a cell size of 50 m, as this is a very large area. Note that RSME does not change when altering the cell size and boundary distance.

Having a buffer (the convex hull distance in the R script) versus a hard boundary (no buffer) around the sites makes minimal difference to the contours, despite the raster looking slightly different around the edges. The raster looks ‘pixelated’ around the edges and ends up cutting out parts of the contours. See the similarity of the contours with buffer (red lines underneath the purple contour layer above) compared to the hard boundary (purple contours) (Figure 47).

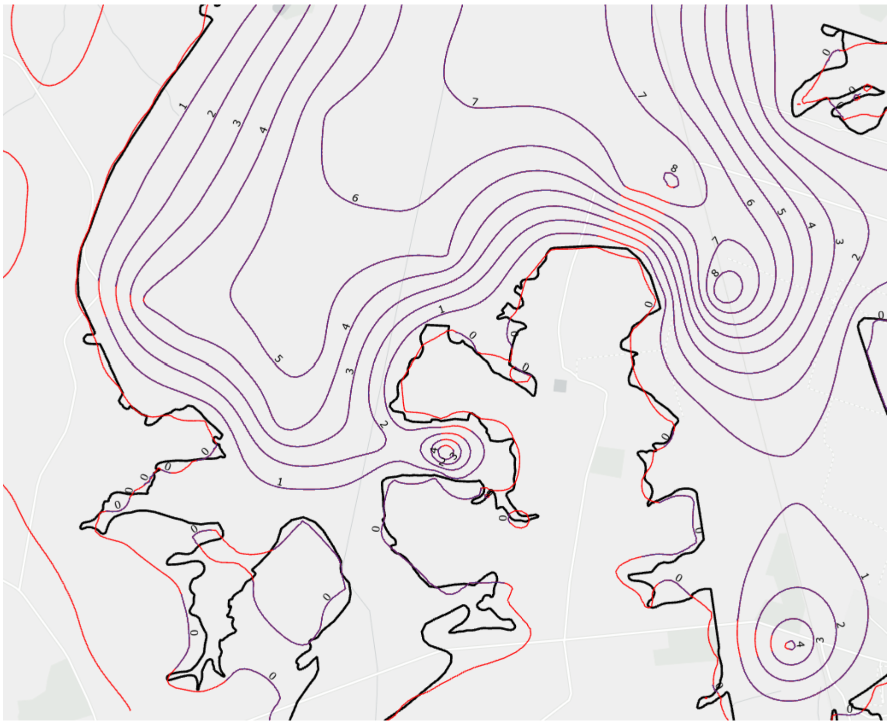


Figure 47. Difference between contours produced with a buffer (red lines) and with a hard boundary (without a buffer) (purple lines). The contours without a buffer are underneath the purple lines, so where there is no purple line the ‘hard boundary’ has ‘cut off’ the contour line.

Like the outer boundaries, the inner boundary lines are converted to points every 200 m along the line and downloaded as a 0.3 m peat thickness site. We experimented with decreasing the distance in between the points and found that contour lines respect the inner boundaries at 50m and 100m more so than 200m, but are still not perfect and the 200 m is less intensive for the model to run in R.

14 Appendix H – Contour adjustment methodology

Following kriging, contour lines were imported into ArcGIS Pro. In several bogs, kriged contours intersected the outer peat boundary or internal geomorphic features (e.g., hills, stream margins). Because peat thickness decreases gradually toward the margins, contours should transition smoothly and remain approximately parallel to these boundaries. To ensure geographically plausible patterns, minor manual edits were applied using the following rules:

1. **Outer boundary intersections**
   - Where contours intersected the peat boundary, vertices were adjusted so the contour aligned parallel to the boundary.
2. **Inner geographic features**
   - The same rule was applied to intersections with internal features such as hill slopes or stream edges.
3. **Sequential adjustment of multiple contours**
   - When several contour lines intersected a boundary (e.g., 1, 2, 3, 4 m), each line was adjusted sequentially to maintain consistent spacing and gradient (e.g., the 2 m line positioned between the edited 1 m and 3 m lines).
4. **No fixed distance rule**
   - Adjustments were guided by local topography and expected peat behaviour rather than a uniform offset distance.

An example of an edited contour segment is shown in Figure 48, where the initial kriged contour (light blue) was adjusted to run parallel to the peat boundary (dark blue).

Figure 48. Two examples of locations where the kriging model has modelled the original contours (light blue line) through a boundary (dark blue line) and the lines require adjustment by editing the vertices (green squares) of the contour line (red dashed line). The left-hand example shows a simple example of just the 1 m contour requiring adjustment. The right-hand example shows a more complex intersection where multiple contours (1 m and 2m contour lines) have intersected the boundary and each contour is sequentially adjusted to maintain consistent spacing.

15 Appendix I –Table of bog information

Table 8. Supplementary information for Table 2, including surrounding geographic features and land uses within bog extent (based on LUCAS).

Bog	Surrounding geographic features (e.g. rivers, streams, hills)	Land uses (LUCAS)
Hauraki (includes Hauraki East and Kopuatai)	Several canals running through; Piako River which flows lengthwise through the centre of Hauraki dividing the peatland into Kopuatai peat dome and Torehape peat Dome; Flax block Wildlife management reserve	71, 74, 75, 76, 78, 79, 80
Hoe o Tainui	Pukemokemoke to the south	71, 74, 75, 79,
Huntly	Lake Waahi, Lake Puketirini, Lake Rotongapoiti, Lake Te Kapa; Te Ranga hill, Pukenui Hill, Rotowaro Opencast mine, Awaroa Swamp wildlife management reserve, Lake Whangape wildlife management reserve, Lake Rotongaro Wildlife management reserve, Lake Okowhao Wildlife management reserve	71-76, 79, 80
Kainui	Lake Hotoananga, Lake Pikopiko, Lakes A, B, C, D,E, Mangatoketoke Stream, Horsham Down wildlife management reserve	71, 74, 75, 78, 79, 80
Komakorau	Pukemokemoke Hill, Mangawhara stream to the North, Motumaoho Hill,	71-75, 77, 78, 81
Moanatuatua	Lake Rotomanuka, Moanatuatua peat scientific reserve, Lake Serpentine Wildlife Management Reserve, Lake Rotopotaka Wildlife management reserve	71, 73-81
Ohinewai	Lake Waikere to the north, Lake Rotokawau, Lake Ohinewai to the west.	71,72, 74, 75, 76, 79, 80, 81
Ohote	Lake Rotokauri, Waiwhakareke Natural heritage park, Horseshoe Lake,	71-76, 78-81 (Country club)
Orini	Taupiri Scientific Reserve, Managwhara stream, Taupiri Range	71, 75
Rukuhia	Hamilton Lake, Lake Maratoto, Lake Ngaroto,	71-81
Te Mimiha	Taupiri Range, Pukemore, Matahuru Stream	71, 74, 75, 78
Whangamarino and Lower Waikato	Mangatawhiri river, Kopako mine, Kopuku stream, Whangamarino River, Maramarua River, Maungaroa, Pukeroa, Whataroa, Long swamp quarry,	71-76, 78-81 (Native bush/swamp, North Island main trunk, Aerodrome)

Land use classification

- 71 - Natural Forest
- 72 - Planted Forest - Pre 1990
- 73 - Post 1989 Forest
- 74 - Grassland - With woody biomass
- 75 - Grassland - High producing
- 76 - Grassland - Low producing
- 77 - Cropland - Orchards and vineyards (peren...
- 78 - Cropland - Annual
- 79 - Wetland - Open water
- 80 - Wetland - Vegetated non forest
- 81 - Settlements or built-up area
- 82 - Other

16 Appendix J – Organic carbon lab results

Table 9. Laboratory results for Organic Matter and Total Carbon for soil samples collected in field. Note the colour coding in key below.

Sample #	Organic Matter	Total Carbon	Average	Bog
1	20.8	12	3.368	Hauraki
2	52.6	30.5	0.424	Hauraki
3	22.1	12.8	0	Hauraki
4	55	31.9	3	Hauraki
5	56.4	32.7	0.15	Hauraki
6	46.1	26.8	0.15	Hauraki
7	53.1	30.8	0.2	Hauraki
8	29.8	17.3	0.47	Hauraki
9	28.8	16.7	0.15	Hauraki
10	22.5	13.1	0.36	Hauraki
11	15.4	8.9	0	Hoe o Tainui
12	41.5	24.1	0.25	Hoe o Tainui
13	49.5	28.7	0	Hoe o Tainui
14	55.5	32.2	0	Kainui
15	23.3	13.5	0	Kainui
16	37.5	21.8	0.554	Kainui
17	14.1	8.2	0.34	Komakorau
18	49.7	28.8	0.25	Komakorau
19	21.7	12.6	0	Komakorau
20	21.7	12.6	0.322	Komakorau
21	43.1	25	0.4	Komakorau
22	24.4	14.2	0.312	Komakorau
23	18.7	10.9	0.318	Komakorau
24	12.7	7.4	0	Komakorau
25	16.9	9.8	0	Komakorau
26	17.9	10.4	0	Komakorau
27	17.6	10.2	0	Komakorau
28	28.8	16.7	0.15	Komakorau
29	41.7	24.2	0	Komakorau
30	21.6	12.5	0	Komakorau
31	10.1	5.9	0	Komakorau
32	12.6	7.3	0.3	Komakorau
33	22.1	12.8	0.256	Komakorau
34	43.3	25.1	0	Komakorau
35	15.7	9.1	0	Moanatuatua
36	17.9	10.4	0.566	Moanatuatua
37	16.9	9.8	0	Ohinewai
38	15.7	9.1	0	Ohote
39	28.5	16.5	0.314	Ohote
40	24.8	14.4	0.396	Ohote
41	47.4	27.5	1.21	Ohote
42	45.3	26.3	0	Orini
43	28.7	16.6	0.23	Rukuhia

44	32.2	18.7	6.975	Rukuhia
45	5.2	3	0.256	Rukuhia
46	5.4	3.1	0.256	Rukuhia
47	6.3	3.6	0.168	Rukuhia
48	8.1	4.7	0	Rukuhia
49	39.3	22.8	2.816	Rukuhia
50	27.1	15.7	3.57	Te Mimiha
51	36.9	21.4	0	Te Mimiha
52	41	23.8	0.3	Whangamarino

KEY			
Colour	**Organic Carbon**	**Organic Matter**	**Combined peat descriptions from Milne (1995) & Hewitt (2010)**
(pink)	<18%	<17%	Non peat
(yellow)		17 - 30%	Slightly peaty silt loam (or other textural class)
(green)		30 - 50%	Sandy or loamy peat (with >50% and <50% sand in mineral fraction, respectively)
	>18%	>50%	Peat

17 Appendix K – Summary statistics and other results

17.1 Bog summary statistics

Table 10 provides the summary statistics (maximum, mean, median, range, quartiles, and sample size) for each Waikato peatland system described in this study. The statistics given in Table 10 are the measured peat thickness results that went into the box plot in Figure 10, while the statistics given in Table 11 are the peat thickness values derived from the modelled raster surface that was used to create the contour maps in Section 13.1.

Table 10. Descriptive statistics for measured peat thickness across Waikato peat bogs. Bogs with low sampling density (n = <10) bogs are indicative only. Statistics are for all measured sites classified as peat (>0.3 m) but the sample size for all measured sites (including non-peat <0.3 m sites) is given also.

Bog	Max	Mean	Median	Min	Q1	Q3	n = excl. <0.3 m	n = incl. <0.3 m
Hauraki	5.95	2.28	2.25	0.34	1.33	3.05	162	256
Hauraki_East	3.52	3.11	2.92	2.89	2.90	3.22	3	5
Hoe o Tainui	9.44	5.41	5.97	0.73	2.79	7.11	14	19
Huntly	8.79	2.90	2.49	0.32	1.32	3.99	266	266
Kainui	5.84	2.21	1.63	0.55	0.87	2.76	26	31
Komakorau	10.54	2.18	1.72	0.30	0.90	3.18	256	289
Kopuatai	12.00	5.02	4.42	0.39	2.15	7.42	106	192
Lower Waikato	7.49	2.22	1.24	0.34	0.41	3.68	52	52
Moanatuatua	11.00	3.65	3.30	0.30	1.71	5.46	200	209
Ohinewai	9.50	6.30	6.78	2.24	4.62	8.16	6	13
Ohote	3.66	2.30	2.34	0.99	1.78	2.94	10	19
Orini	8.19	4.98	4.63	0.99	3.68	6.68	26	28
Rukuhia	11.10	6.05	6.67	0.33	4.52	7.78	191	202
Te Mimiha	11.76	8.01	7.63	3.08	7.39	10.18	5	7

Table 11. Descriptive statistics for modelled peat thickness across Waikato peat bogs. Number of sites (n) is large as it represents the number of points generated by the 25 m cell raster surface. Non-peat (<0.3 m) values are included because these are necessary for running the model.

Bog	Max	Mean	Median	Min	Q1	Q3	n = including <0.3 m
Hauraki	5.58	1.28	0.79	0	0.25	2.33	222432
Hauraki_East	3.54	0.88	0.56	0	0.22	1.51	10976
Hoe o Tainui	7.83	1.97	0.83	0	0.32	3.3	41671
Huntly	7.79	1.58	1.27	0	0.66	2.3	24883
Kainui	4.66	0.63	0.35	0	0.29	0.6	61642
Komakorau	5.03	1.09	0.63	0	0.29	1.61	124917
Kopuatai	12.01	3.11	1.48	0	0.13	6.08	293137
Lower Waikato	NA	NA	NA	NA	NA	NA	NA
Moanatuatua	10.28	2.03	0.88	0	0.29	3.32	193037
Ohinewai	2.36	0.5	0.35	0	0.29	0.58	44658
Ohote	3.58	0.53	0.32	0	0.27	0.49	17021
Orini	8.14	2.74	2.09	0	0.5	4.79	32451
Rukuhia	9.93	2.67	0.99	0	0.31	5.36	158214
Te Mimiha	7	1.45	0.59	0	0.23	2	30859

17.2 Von Post

The bar chart in Figure 49 shows the mean Von Post humification value for each surveyed bog. Each bog is represented by a differently coloured bar, allowing comparison of average peat decomposition among sites. Bogs such as Kainui, Komakorau, and Moanatuatua show higher average Von Post scores, indicating more decomposed peat on average, whereas others such as Hauraki_East, Te Mimiha, and Kopuatai show lower values.

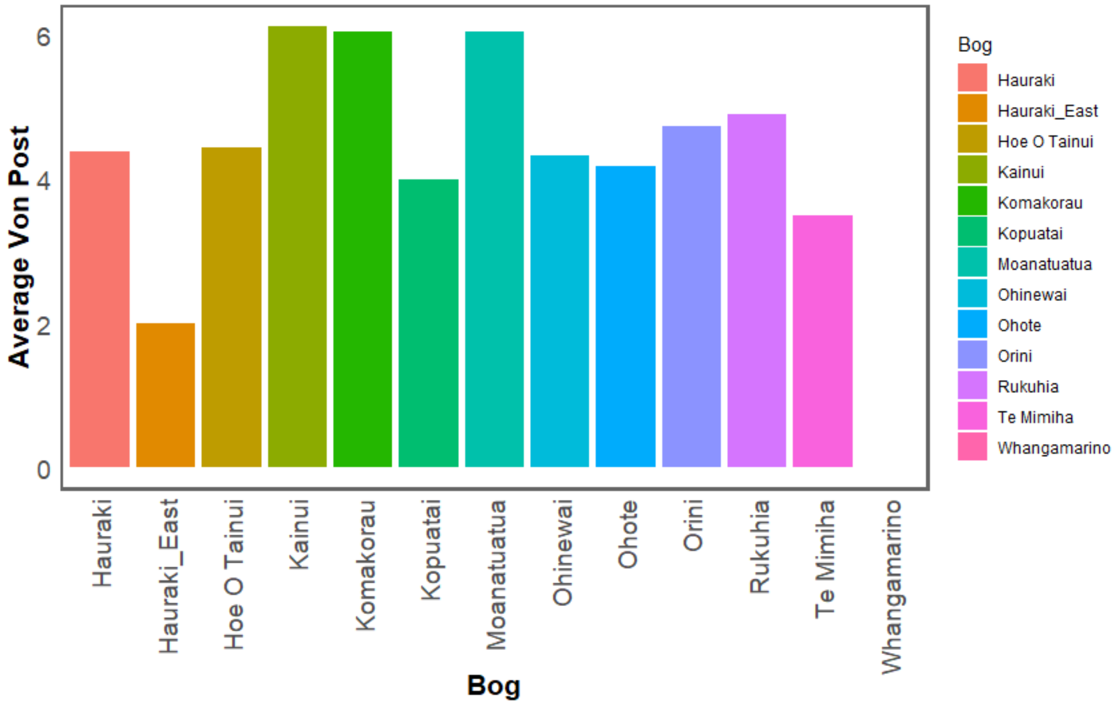


Figure 49. Average Von Post humification score for each bog from 2023 survey only.

17.3 Organic matter

The scatterplot in Figure 50 illustrates how total carbon content changes with soil sampling depth. Like organic matter, total carbon increases modestly with depth, as shown by the positive regression line and its 95% confidence interval. A red dashed line marks the threshold value used for classifying soil carbon levels.

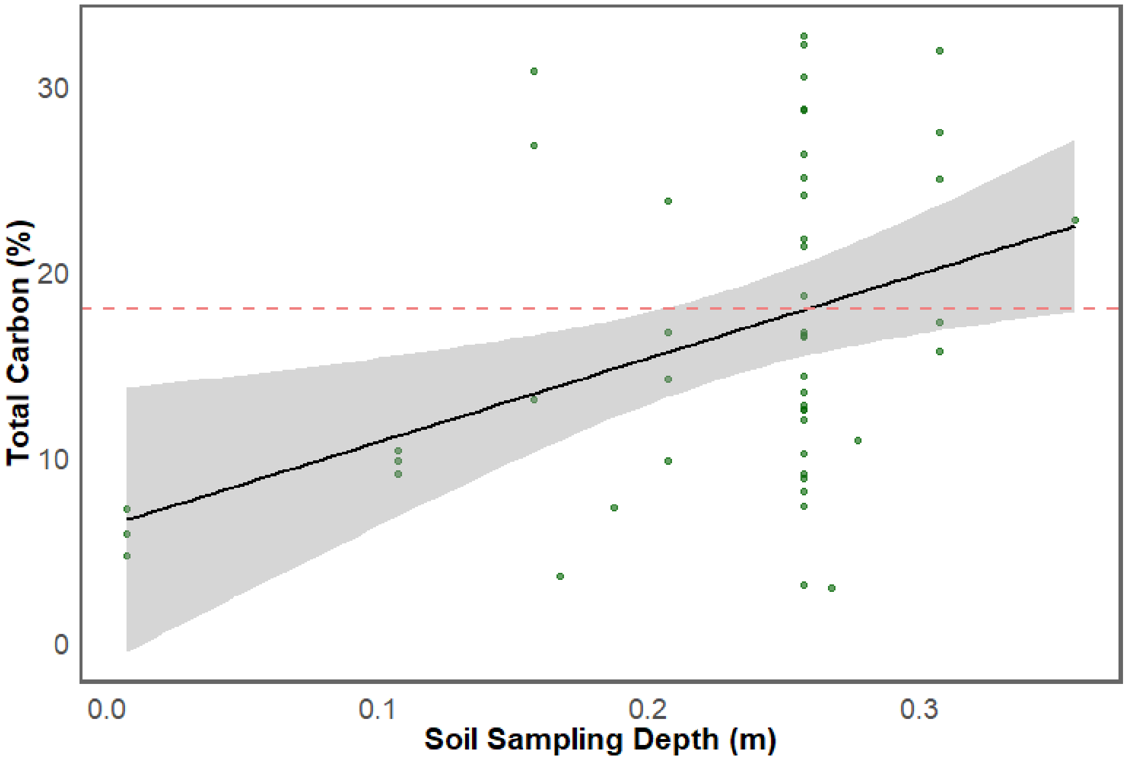


Figure 50. Relationship between soil sampling depth and total carbon content. Green points represent individual measurements, and the black regression line with grey 95% confidence band indicates a positive association with depth. The red dashed line shows the 18% carbon threshold from Hewitt (2010).

The scatterplot in Figure 51 shows the relationship between soil sampling depth and measured organic matter content. A positive trend is visible, with organic matter increasing slightly with depth. The fitted regression line (with 95% confidence band) highlights this upward trend. Red dashed lines indicate organic matter threshold values used for interpretation.

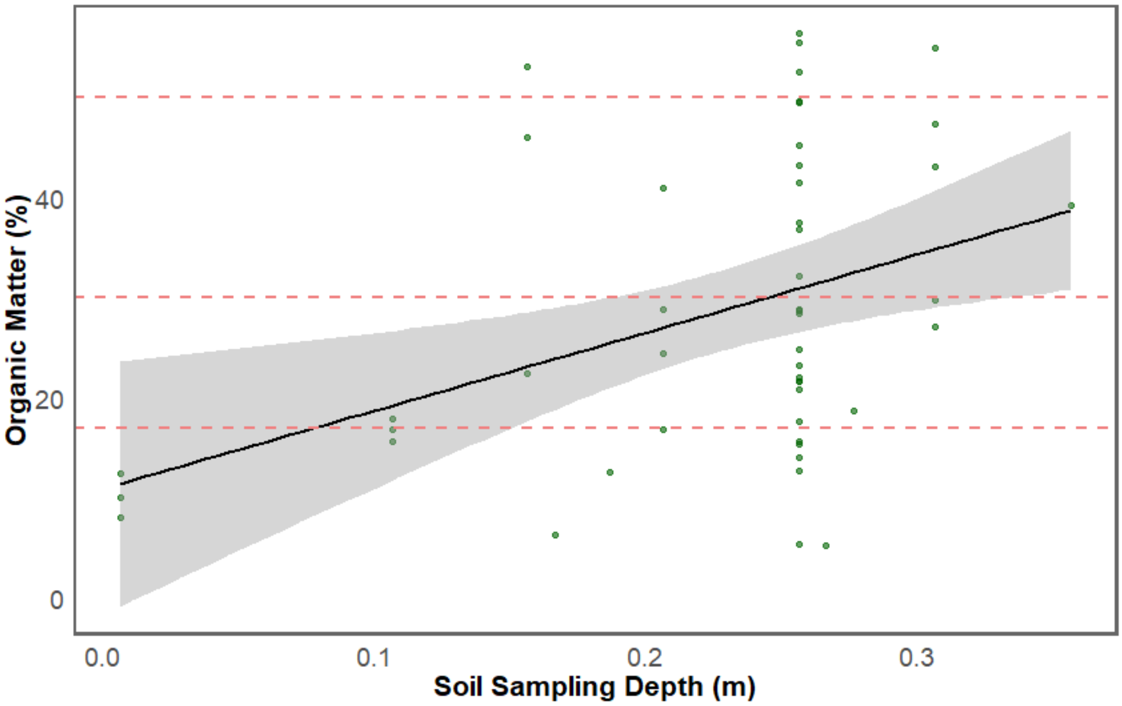


Figure 51. Relationship between soil sampling depth and organic matter content. Individual samples are shown as green points, with a fitted linear regression line and 95% confidence interval (grey band). Red dashed lines denote organic matter status description thresholds from Milne (1995).

17.4 Underlying material

The composition of materials underlying peat deposits was largely undescribed (27%), but for those sites where a description was included, blue clay was most popular (23%) (Figure 52). Other notable materials include beige silt (16%) and beige clay (12%), followed by instances of brown clay (6%), beige sand (4%), and brown silt (4%). Minor observations of blue green clay, beige silty clay, and grey clay each represent approximately 3% of the total. This distribution indicates that clay-rich substrates, particularly blue and beige clays, are prevalent beneath peat layers, while sands and silts occur less frequently. Substratum material may affect hydrologic retention and informs us about the historic environment that caused peat to form in this location.

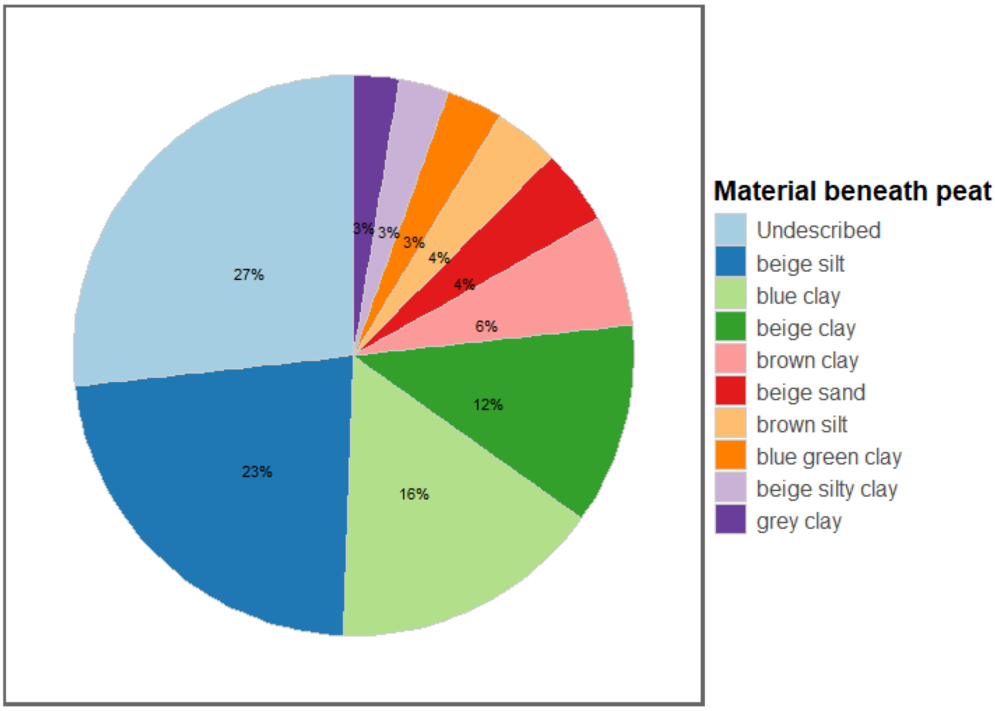


Figure 52. Proportion of materials underlying peat deposits across measurement sites as described in field comments.

18 Appendix L – GIS layers

This appendix lists all GIS datasets used in the analysis, separated into publicly available layers and licensed/internal datasets. Metadata includes the dataset name, provider, version/date accessed, purpose in the study, and any relevant notes about usage limitations. Publicly available layers were used where national datasets existed (e.g., S-Map). Internal layers were used where no public equivalents were available or where project-specific data (e.g., field-collected peat thickness measurements, created peat contour layers) were required to improve spatial accuracy and display results.

18.1 Publicly available layers

These GIS layers are accessible from public agencies or national data repositories. They can be obtained directly through the referenced sources.

Table 12. Publicly available GIS datasets used in this study.

Dataset name	Provider/source	Version /access date	Scale/resolution	Purpose	URL
S-Map Soil Spatial Database	Manaaki Whenua Landcare Research	v5.4 (Aug 2022 update)	1:50,000 All of New Zealand	Identify Organic Soils	https://lris.scinfo.org.nz/layer/111207-smap-soil-classification-soil-order-dec-2022/ https://smap.landcareresearch.co.nz/
Fundamental Soils Layer	Manaaki Whenua Landcare Research	v10 (North Island)	1:50,000	Historic soil mapping; organic soil context and legacy peat boundaries	https://lris.scinfo.org.nz/layer/48136-fsl-north-island-v10-all-attributes/
Wells and Stratum Information (Waikato & NZ)	Waikato Regional Council, LINZ-hosted ArcGIS Online	Accessed 2024	Point data	Support for peat depth inference and site characterisation	https://www.arcgis.com/home/item.html?id=60a7488987214cacb53c636f3165d740 https://data.waikatoregion.govt.nz:8443/ords/piplx/f?p=140:12:0::NO::P12_METADATA_ID:11978
LiDAR – Waikato Region	Waikato Regional Council	2016 – 2022 releases	0.5–1 m	High-resolution elevation for surface modelling, subsidence patterns, and QC of point locations	https://data.waikatoregion.govt.nz:8443/ords/piplx/r/it/data-catalogue-public/metadata-html-display?p12_metadata_id=12940
Property parcels – Waikato Region	LINZ	Accessed 2022	Cadastral polygons	Used for property-specific maps and locating thickness measurement sites	https://data.waikatoregion.govt.nz:8443/ords/piplx/r/it/data-catalogue-public/metadata-html-display?p12_metadata_id=12998
Davoren 1978 peat thickness contours – Waikato Region	Davoren (1978) digitised by Waikato Regional Council	for the Waikato Region	Historic mapping, accessed 2022	Historic comparison, site selection, support for boundary refinement and peatland extent interpretation.*	https://data.waikatoregion.govt.nz:8443/ords/piplx/r/it/data-catalogue-public/metadata-html-display?p12_metadata_id=8197

* The original Davoren (1978) survey did not include recoverable digital coordinates for peat thickness measurement sites. Site locations used in this study were derived from maps georeferenced and digitised in ArcMap in 2017 by Waikato Regional Council staff. Documentation of the georeferencing workflow, including control points, transformation type, and RMSE, is not available. Consequently, positional uncertainty cannot be quantified directly. However, any inherited positional uncertainty is considered small relative to the scale of the peatland systems and unlikely to materially influence peat thickness patterns or contour outputs.

18.2 Licenced and internal layers

These layers are not publicly accessible and include datasets created during this project or held internally by the organisation. Restricted datasets should be noted accordingly.

Table 13. Private and in-house GIS datasets used in this study.

Dataset name	Provider/source	Version/access date	Description	Purpose	Access/restrictions
AgriBASE (Waikato Region subset)	AsureQuality (licensed)	Updated annually	National rural property and land-use database	Provides property-level land use and landowner information	Paid subscription; not publicly accessible
2023 Peat Depth/Thickness Survey Points	Waikato Regional Council	2023	Dutch-auger and probe depth measurements collected during this study	Used for thickness modelling, boundary refinement, and validating historic datasets	Internal dataset; released only as *Supplementary Material S1* (if approved)
Revised Organic Soil / Peat Boundary	This study (intersection of S-Map, FSL, Davoren, and 2023 sites)	2025	Project-specific boundary created for all bogs	Used as the final Organic Soils boundary for analysis and mapping	Project-specific; internal unless published
Peat Thickness Contours (modelled)	This study	2025	Contours generated from 2023 field sites using GIS tools (Appendix: R script and ArcGIS contour workflow)	Visualisation of thickness gradients and interpolation	Internal; derived dataset