Remotely piloted aircraft system (RPAS) survey and habitat assessment of Ruakaka Estuary

Northland
REGIONAL COUNCIL

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1 Introduction

1.1 Sedimentation

The New Zealand Coastal Policy Statement 2010 (NZCPS), and The Regional Policy Statement for Northland 2016 (RPS) both identify sedimentation as a key issue affecting the coastal environment, and outline policies and methods to monitor and reduce sedimentation rates.

Northland Regional Council (Council) has previously commissioned research to investigate historical sedimentation rates in the Kaipara Harbour (Swales *et al.* 2011), Bay of Islands (Swales *et al.* 2012) and Whangarei Harbour (Swales *et al.* 2013). This research involved radioisotope analysis of sediment cores to determine historical sediment accumulation rates.

Council has also installed sediment plates at its estuary monitoring sites to monitor current sediment accumulation rates. This method involves burying sediment plates and measuring the depth of sediment above these plates at regular intervals. One limitation of this approach is that the information is very spatially restricted. Sediment may be accumulating rapidly in one part of an estuary but may be accumulating more slowly (or even eroding) elsewhere in the estuary. Data, from the two plates currently installed in Ruakaka Estuary, recorded sediment accumulation rates of 2mm and 5mm per year between 2009 and 2018. To account for spatial variation, a large number of plates would be required to monitor sedimentation rates at an estuary-wide scale.

The present study investigates the use of remote piloted aircraft system (RPAS) technology and photogrammetry to collect baseline elevation data on an estuary-wide scale. From this preliminary study, future surveys could be undertaken to determine if sediment has accumulated within an estuary.

1.2 Indigenous ecosystems and biodiversity

The NZCPS and the RPS include policies to protect or enhance indigenous ecosystems and biological diversity in the coastal environment. Understanding the current status and extent of our indigenous ecosystems is an important step to Council meeting these statutory requirements.

Council currently conducts regular ecological monitoring at sentinel sites in Whangarei Harbour, Arapaoa River, Whangaroa Harbour, Kerikeri Inlet and Ruakaka Estuary (Griffiths, 2011) and has also undertaken 'one-off' ecological surveys of the Whangarei Harbour (Griffiths, 2012), the Kaipara Harbour (Griffiths, 2014), the Waitangi Estuary (Griffiths, 2013), Ngunguru Estuary (Parkes *et al.,* 2016) and Mangonui Harbour (McCartain & Hewitt, 2016). While these programmes provide detailed information about ecological communities and species present at individual sites, they do not provide information about the ecological communities at an estuary scale.

The present study investigates the use of RPAS technology to facilitate rapid estuary-scale habitat surveys. This will help Council to assess the effectiveness of its policies and rules in the Proposed Regional Plan (PRP) to protect indigenous biodiversity and marine significant ecological areas (SEA).

1.3 Ruakaka Estuary

Ruakaka Estuary is a drowned river valley system located on Northland's east coast. The Estuary comprises a main river channel, which meanders north to south, an outer lagoon and a southern spur (Figure 1).

The main Ruakaka River channel is bordered by narrow sand and mud flats with fringing mangroves and saltmarsh habitat. The outer lagoon comprises shifting sand bars and channels, with a sand spit at the entrance to the estuary. There are narrow sand flats on the northern shore and a larger sand flat on the southern shore. The southern spur comprises a shallow channel that meanders south to north. The channel is boarded by sand flats, saltmarsh and mangrove habitat, with a more expansive sand flat, at the northern end, where the spur joins the main river channel.

Ruakaka Estuary has been identified in the PRP as a significant ecological area (SEA). The assessment identified that the estuary contained intact ecological sequences, provides and contributes to ecological linkages, provides network and buffering functions and supports the life stages of indigenous fauna including benthic invertebrates, fish and shorebirds.

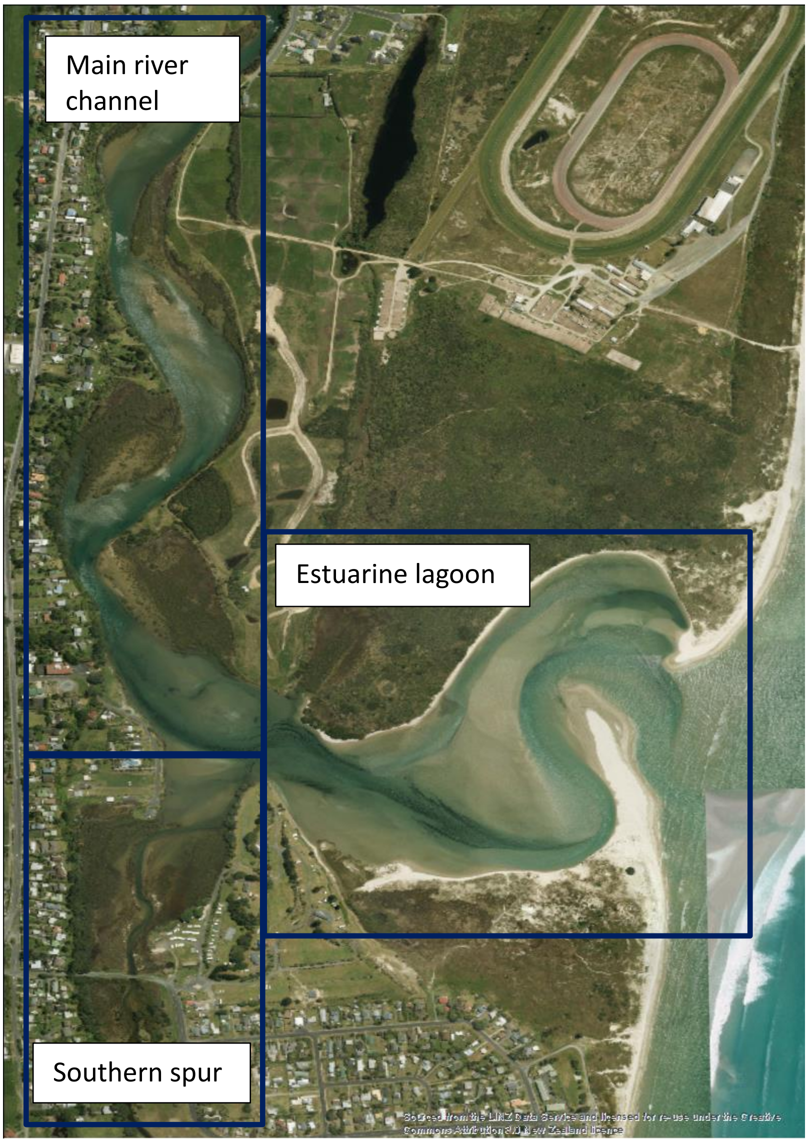

Figure 1. Aerial view of Ruakaka Estuary.

2 Methods

2.1 Aerial image acquisition

2.1.1 Remotely piloted aircraft system (RPAS)

Aerial images were obtained using a DJI Phantom 3 Advanced remotely piloted aircraft system (RPAS), equipped with a FC300S camera. The flight plans were planned and operated using DroneDeploy software, installed on an iPad Air 2. Due to RPAS battery life and the requirement to maintain line of sight with the RPAS, the estuary was divided into seven flight zones (Figure 2). The image resolution was set to 18MP. The front lap settings were set to 75% and the side lap settings were 65%.

Due to the designation of Ruakaka Estuary as a wildlife reserve, the Department of Conservation (DOC) requested that RPAS flights did not take place until April, when breeding birds had departed the estuary. RPAS flights were initially scheduled for low tides between 10:00 and 16:00 over two days (16th April & 17th April 2018). Unfortunately, due to technical difficulties with the RPAS and the software, the flight on the 16th April was abandoned before any flights were completed. RPAS flights were undertaken over low tides on 17th and 27th April and 1st May (Table 1).

Table 1. RPAS flight dates and times for Ruakaka Estuary surveys.

Flight zone	Date	Time (NZST)	Images
1	17/04/2018	14:59-15:08	258
2	17/04/2018	15:26–15:59	481
3	27/4/2018	11:23-11:25	69
4	17/04/2018	13:59-14:06	197
5	1/05/2018	14:37-14:44	202
6	1/5/2018	15:25-15:34	267
7	1/5/2018	16:13-16:16	71

2.1.2 Ground control points (GCPs)

A Trimble R10 RTK GNSS system was used to collect 71 ground control points (GCPs) (Figure 2) for geo-referencing and correcting the elevation data produced in DroneDeploy. The base was positioned over LINZ benchmark BDDM at Princes Road, Ruakaka (a 4th order mark) and the rover was used to collect a measurement to a second known LINZ control point to verify the location of the base. GCPs were then collected throughout the estuary, on flat uniform surfaces. They were marked with a cross on the ground and the centre of each GCP was surveyed with the rover. At each GCP, three GPS measurements were recorded and these were then averaged.

The co-ordinate system used for the survey was New Zealand/NZGD2000, Mount Eden. The vertical adjustment used the Geoid model NZOtp16. The collected GPS data was quality checked in Trimble Business Centre and exported.

In total 71 GCPs were collected. As DroneDeploy only allows for up to 30 GCPs to be used in processing the remaining RTK GPS survey points were utilised as check points.

DroneDeploy recommends that GCPs are located at least 15m from the edge of the planned flight path and 15m away from water. GCPs located too close to the perimeter of the flight path are likely to be captured in less images collected by the RPAS (each GCP needs to be visible in at least three images to be used for processing). Unfortunately, due to the shape of some parts of the estuary, it was not always possible to place GCPs 15m away from a water body or the perimeter of the flight plan.

2.1.3 DroneDeploy

After the completion of the flights, all photographs and a CSV file of GCPs was uploaded to DroneDeploy. DroneDeploy, identifies which photographs a GCP should be located in and then requires the user to manually identify the centre of the GCP in each photograph. Of the 30 GCPs that were uploaded for processing, four caused an unknown error with the DroneDeploy software so could not be used. A further five GCPs were only visible in two or fewer images so were not included for processing. In total 21 GCPs were used (Figure 3). The remaining RTK GPS survey points were used to check the accuracy of the outputs.

After processing an orthomosaic GeoTiff, a digital elevation model (DEM) GeoTiff and a contour shapefile, with a resolution of 0.25m, was exported from DroneDeploy.

The DEM GeoTiff and a CSV of the RTK GPS survey check points were uploaded to ArcGIS 10.6, in order to calculate the accuracy of the DEM. The 'add surface information' tool in ArcGIS was used to add the z value (elevation) from the DEM to the point feature created from the CSV of the RTK GPS survey check points. The difference was then calculated between the two elevations to assess the accuracy of the DEM.

Figure 2. Flight zones and RTK GPS survey points.

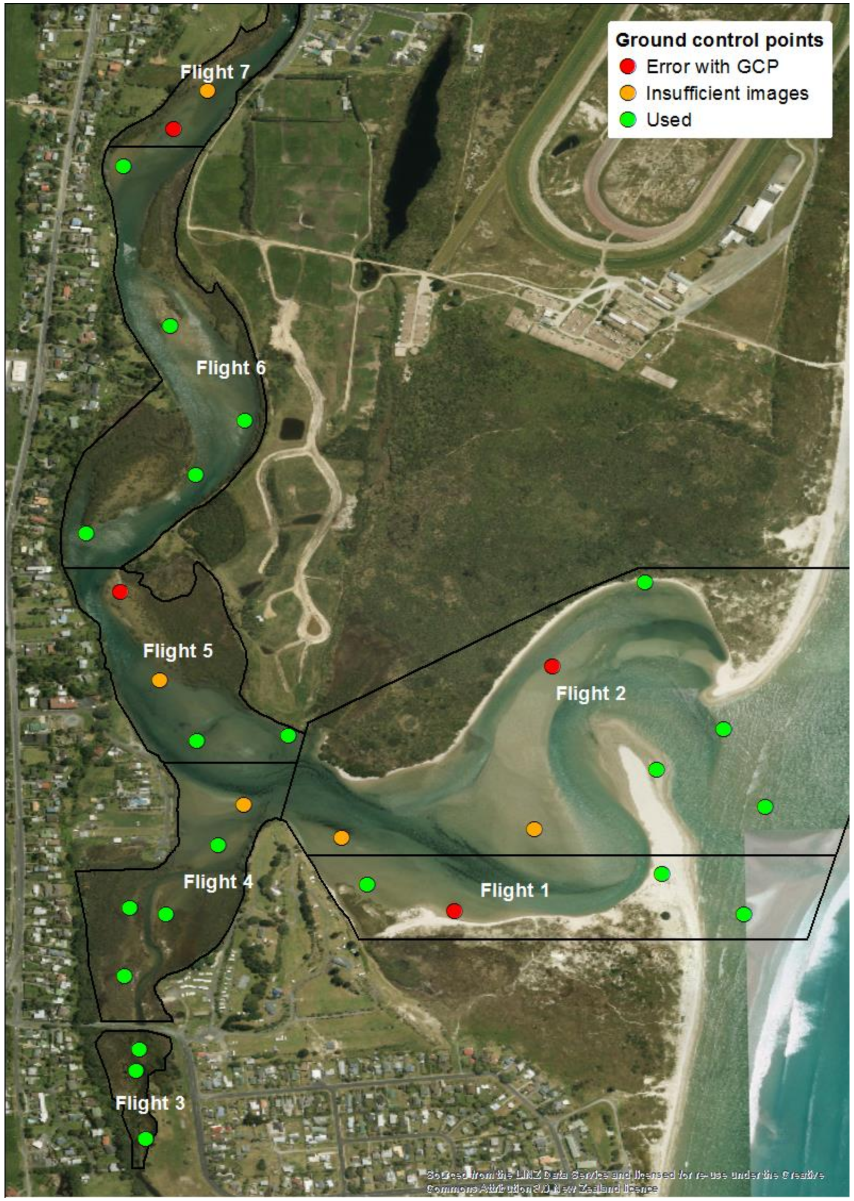

Figure 3. Ground Control Points uploaded to DroneDeploy.

2.2 Habitat Survey

2.2.1 Field techniques

Field staff walked in transects approximately 30m apart and stopped to record substrate and habitat features every 30m. If obvious boundaries were encountered between points, additional features were recorded. Where practical, boundaries between substrate classes or habitats were recoded as either a polyline or a polygon feature.

2.2.2 Collector

All observations were recorded using the Collector app installed on iPad Air 2 devices. The Collector app allows for point features, polyline features and polygon feature to be recorded. A project was created within the Collector app, with four attributes for each feature. Three attributes 'Substrate', 'Flora' and 'Fauna' contained pre-populated drop down categories (Appendix 1) and a fourth attribute 'Comments' was given a free text field. The app automatically collects a date stamp, the name of the user logged into the app and the GPS location for each feature. Geotagged photographs were also taken to assist with habitat mapping, using the camera on the iPad Air 2 devices.

2.3 Habitat classifications

2.3.1 Substrate

At each point the substrate was classified into one of eight categories (Table 2). These categories were adapted from the sediment categories in the Estuary Monitoring Protocol (Robertson *et al*., 2002) and an intertidal habitat survey of Waikato estuaries conducted by Needham *et al.* (Needham *et al.,* 2013).

2.3.2 Flora

At each point the vegetative cover 'flora' was recorded using one of ten categories (Table 3) and the dominant taxa recorded in the comments attribute. This classification system was based on Level III (structural class) and Level IV (dominant Cover) of the Atkinson System (Atkinson, 1985), described in the Estuary Monitoring Protocol (Robertson *et al*., 2002).

2.3.4 Fauna

At each point the fauna was recorded using 14 categories (Table 4). The classification system was adapted from Needham *et al*. (Needham *et al*., 2013). One difference between Needham's classification and the classification used in this study was that additional categories were included for juvenile cockles (*Austrovenus stutchburyi*), juvenile pipi (*Paphies australis*) and juvenile *Macomona liliana*. Another difference was the addition of a low density category for cockles and pipi and differences in the shell lengths for adult cockle and pipi categories.

Needham's classification system defines a 'high density cockle' or 'high density pipi habitat' if 10 or more adults are found in a 15 x 15cm area. We retained the requirement for 10 or more individuals for high density categories but also included a low density category. The low density categories were based on a system of ecological classification rules developed by Hewitt and Funnel (Hewitt & Funnel, 2005), in their survey of benthic habitats in the southern Kaipara Harbour, which was also used by Griffiths (Griffiths, 2014) in a survey of the northern Kaipara Harbour. Hewitt and Funnell (Hewitt & Funnel,

2005) classified cockle and pipi habitat if densities were greater than 226 individuals per square metre. Densities of five or more individuals per 15 x 15cm area were therefore used to classify low density cockle and low density pipi habitat (222 individuals per square metre).

In the classification system used for this study, cockles 15mm or greater in shell length and pipis 18mm or greater in length were classified as adults. In a survey of pipis and cockles in Northland, for the Ministry of Primary Industries (MPI), Pawley & Smith (Pawley & Smith, 2014) classified cockles smaller than 15mm and pipi smaller than 18mm as 'recent recruits', i.e. less than one year old. Utilising these lengths, which were based on growth parameters for each species, allows for comparison with shellfish surveys conducted by MPI.

We also included additional categories for *Cominella glandiformis* and *Zeacumantus lutulentus*. For both these categories we used the same density criteria as Needham *et al*. (Needham *et al*., 2013) for high density *Amphibola crenata* (10 individuals or more per 0.25 m^2).

Our classification system also allowed for multiple categories to be recorded at each point. Therefore, our classification system enabled both juvenile habitat and adult habitat to be recorded at a location if both criteria were satisfied.

Table 2. Substrate categories.

Substrate categories	Description
Very soft mud	The surface appears brown with a black anaerobic layer below. When walking on the substrate you sink more than 5cm.
Soft mud	The surface appears brown with a black anaerobic layer below. When walking on the substrate you sink 2-5cm.
Firm mud/sand	A mixture of mud and sand, the surface appears brown with a black anaerobic layer below. When walking on the substrate you sink 0-2cm.
Firm sand	Firm sand flats may be mud-like in appearance but are granular when rubbed between the fingers, and solid enough to support an adult's weight without sinking more than 1-2cm.
Mobile sand	The substrate is clearly recognised by the granular beach sand appearance and the often rippled surface layer. Mobile sand is continually being moved by strong tidal currents and often forms bars and beaches. When walking on the substrate you sink less than 1cm.
Soft sand	Substrate containing greater than 99% sand. When walking on the substrate you sink more than 2cm.
Very soft sand	Substrate containing greater than 99% sand. When walking on the substrate you sink more than 5cm.
Gravelfield	Sediment characterised by unconsolidated gravel (2-20mm diameter). Visually observed to cover ~70-100% of sediment surface to the extent that very little (or none) of the underlying sediment is visible.

Adapted from Robertson et al., 2002 and Needham et al., 2013.

Table 3. Habitat classes for flora.

Flora categories	Description
Seagrass	Dense vegetation spanning more than $1m^2$. A distinct bed rather than a collection of sparse single leaves.
Mangrove adults	Adult mangrove plants more than 60cm tall.
Mangrove juveniles	Mangroves plants less than 60cm tall.
Grassland	Vegetation in which the cover of grass in the canopy is 20-100% and in which the grass cover exceeds that of any other growth form or bare ground.
Herbfield	Vegetation in which the cover of herbs in the canopy is 20-100% and in which the herb cover exceeds that of any other growth form or bare ground.
Reedland	Vegetation in which the cover of reeds in the canopy is 20-100% and in which the reed cover exceeds that of any other growth form or open water.
Rushland	Vegetation in which the cover of rushes in the canopy is 20-100% and in which the rush cover exceeds that of any other growth form or bare ground.
Sedgeland	Vegetation in which the cover of sedges in the canopy is 20-100% and in which the sedge cover exceeds that of any other growth form or bare ground.
Scrub	Woody vegetation in which the cover of shrubs and trees in the canopy is > 80% and in which shrub cover exceeds that of trees. Shrubs are woody plants < 10cm diameter at breast height.
Tussockland	Vegetation in which the cover of tussocks in the canopy is 20-100% and in which the tussock cover exceeds that of any other growth form or bare ground.

Adapted from Robertson *et al*., 2002.

Table 4. Habitat categories for fauna.

Habitat	Description
Juvenile cockles	≥5 individual sized <15mm shell length per 15 x 15cm area
Low density cockles	≥5 individual sized ≥15mm shell length per 15 x 15cm area
High density cockles	≥10 individuals sized ≥15mm shell length per 15 x 15cm area, or >3 individuals sized ≥30mm shell length per 15 x 15cm area.
Juvenile pipi	≥5 individual sized <18mm shell length per 15 x 15cm area
Low density pipi	≥5 individuals sized ≥18mm (shell length) per a 15 x 15cm area.
High density pipi	≥10 individuals sized ≥18mm (shell length) per a 15 x 15cm area. Typically associated with some shell-hash.
Juvenile *Macomona liliana*	≥4 individual sized <30mm shell length per 15 x 15cm area
High density *Macomona liliana*	≥4 individuals sized ≥30mm (shell length) from a 15 x 15cm area.
Oysters	Covering greater than 50% of the 0.25m^2 quadrat. Must be repeatable over an area >10m in one dimension.
Crustacean burrows	≥10 burrows in a 0.25 m^2 quadrat. Repeated, randomly thrown quadrats must exceed the density threshold.
Low density	Sparse fauna often in densities lower than 1 individual per 0.25 m^2 quadrat.
Diloma subrostratum	10 individuals per 0.25 m^2 were present in 3 or more random quadrats with a spatial extent of ≥10 m in any one direction.
Amphibola crenata	10 individuals per 0.25 m^2 were present in 3 or more random quadrats with a spatial extent of ≥10 m in any one direction.
Zeacumantus lutulentus	10 individuals per 0.25 m^2 were present in 3 or more random quadrats with a spatial extent of ≥10 m in any one direction.

Adapted from Robertson *et al*., 2002 and Needham *et al*., 2013.

2.4 GIS mapping

The features recorded in the Collector app were imported into ArcGIS. All the geotagged photographs were added to the project using the 'geotagged photo to points' data management tool in ArcGIS. The georeferenced orthomosaic GeoTiff, the DEM GeoTiff and the contour polyline shapefile, created in DroneDeploy, were also uploaded to ArcGIS to assist with the delineation of substrates and habitat features.

All map features were created in ArcGIS 10.6. The substrate, flora and fauna features were hand digitalised using information from the collector features, the georeferenced photographs and field notes. A number of substrate and habitat features, were also easily identifiable from the orthomosaic GeoTiff of the Estuary. This image was used extensively to determine the boundaries of features such as mangrove and saltmarsh habitats. The DEM and the contour shapefile features also assisted in determining the boundaries for some features. Features were hand digitalised at a scale of 1:200.

2.5 Habitat preferences

The 'add surface information' tool in ArcGIS was used to add DEM derived z values (elevation) to the point features collected using the Collector app. This enabled analysis of the substrate type and elevation data for each point feature.

3 Results

3.1 Image and Elevation outputs

A total of 1545 images were used by DroneDeploy to create a single orthomosaic GeoTiff (Figure 4). Although the maximum resolution available was 3.37cm/pixel the file size was too large to export so the final resolution was 5cm/pixel. The total area captured by the orthomosaic GeoTiff was 87,5496m^2. The accuracy report issued by DroneDeploy gave the image stitching 100% (excellent) and the average number of images per pixel 10.8 (excellent). The total (RMSE) of the x error was 28mm, the y error was 20mm and the z error was 23mm. The DEM GeoTiff exported form Drone deploy had a resolution of 13.50cm/pixel (Figure 5). The contour polyline shapefile was exported with a resolution of 0.25 metres (Figure 6). It should be noted that the elevation for areas covered by water at the time of the RPAS survey will be inaccurate.

3.2 Ground control points

The minimum and maximum horizontal precision of all 71 RTK surveyed points was 11mm and 40mm, and the minimum and maximum vertical precision was 13mm and 61mm. The mean vertical precision was 30mm (Appendix 2). Of the 21 GCPs used for processing in DroneDeploy, the mean x error was 194mm, the mean Y error was 170mm and the z error was 181mm (Appendix 3).

Of the 50 RTK survey points, that were not used for processing in DroneDeploy, the mean difference between the DEM z value and the RTK elevation was 102mm (Table 5). The minimum difference was 1mm and the largest difference was 300mm (Appendix 3). The elevation model appears to be most accurate for zones 3, 4, 5 and 6, which are all located in the main river channel section or the estuary and the southern spur (Table 5 and Figure 7). All of these zones had a mean difference between the DEM derived z values and the RTK GPS surveyed elevations of < 90mm.

Zone 7 had no GCPs so the poor agreement of the DEM and RTK GPS data in this area was not unexpected. The poor agreement in flight zones 1 and 2 may have been due to the relatively low number of GCPs in these zones.

Table 5. Differences in elevation between RTK GPS elevation and DEM derived z values for check points.

Flight zone	No. of check points	Minimum difference (mm)	Max difference (mm)	Mean difference (mm)
1	4	113	278	17.8
2	6	50	300	18.3
3	2	33	105	6.9
4	8	7	90	2.9
5	17	1	134	7. 1
6	9	6	210	9.0
7	4	145	262	21.5
Total	50	1	300	10.2

Figure 4. Orthomosaic GeoTiff of Ruakaka Estuary.

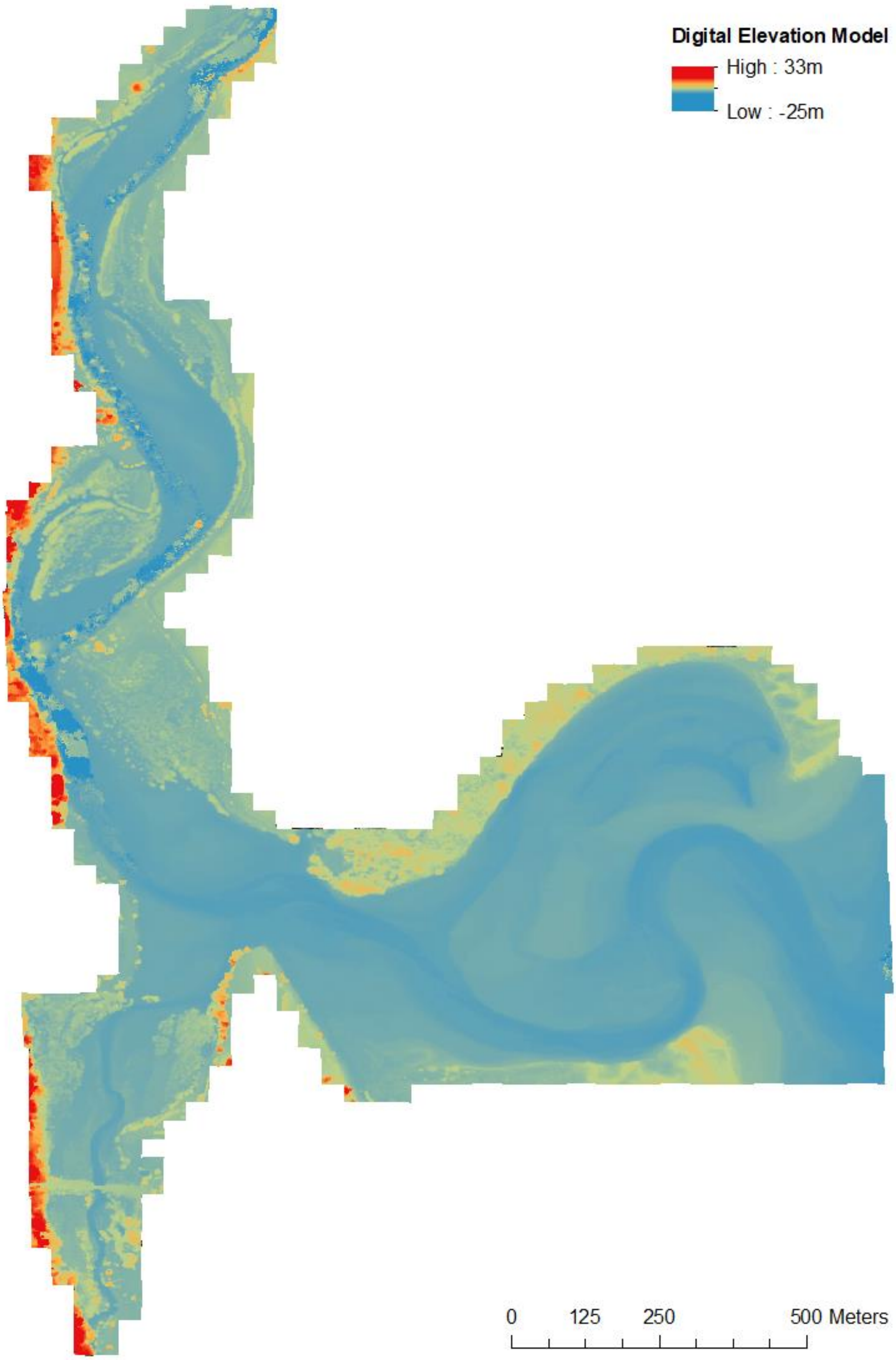

Figure 5. DEM GeoTiff of Ruakaka Estuary. Note: The elevation of areas covered by water at the time of the RPAS survey will be inaccurate.

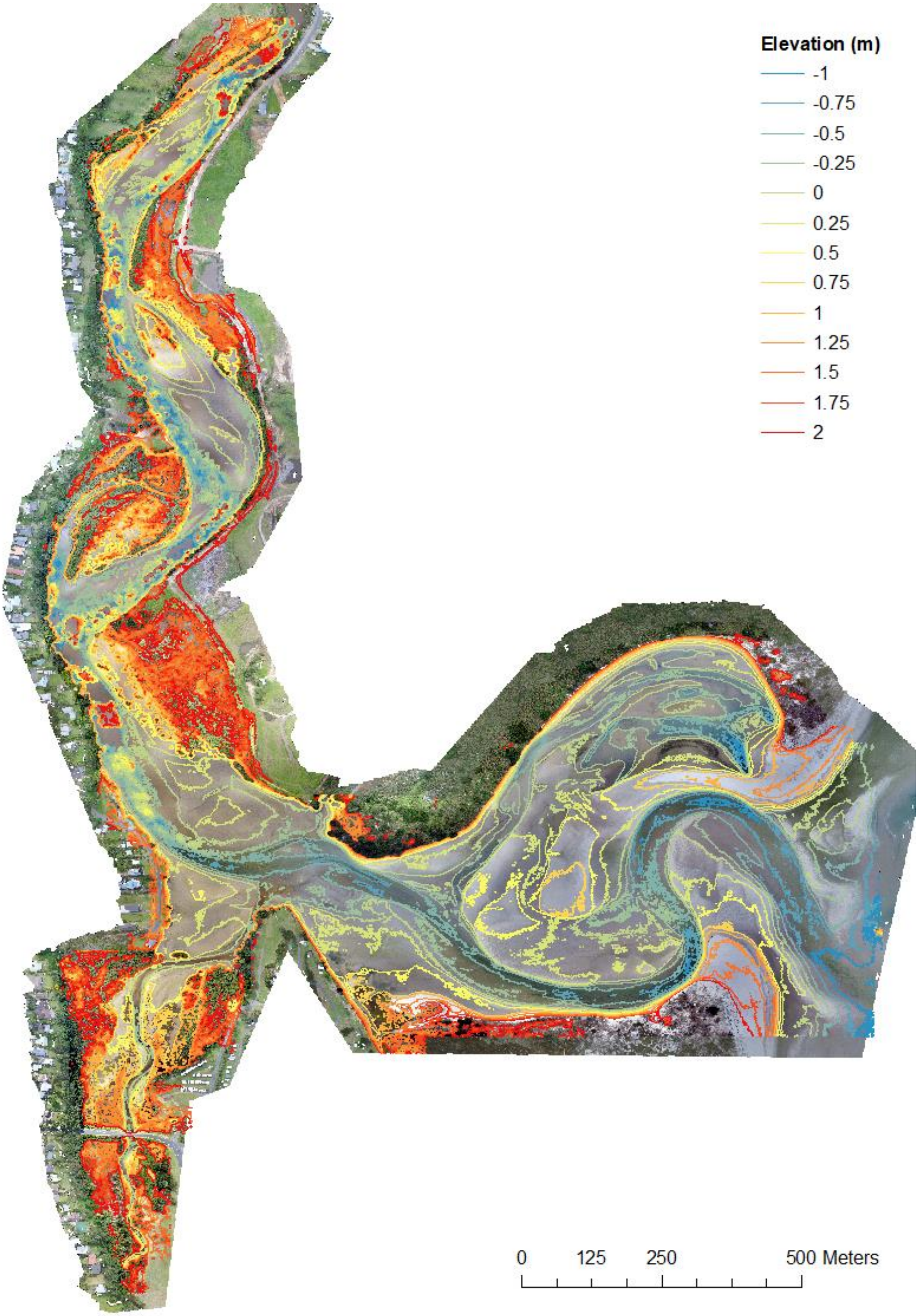

Figure 6. Contour shapefile (0.25m interval) overlaying orthomosaic GeoTiff of Ruakaka Estuary. Note: The elevation of areas covered by water at the time of the RPAS survey will be inaccurate.

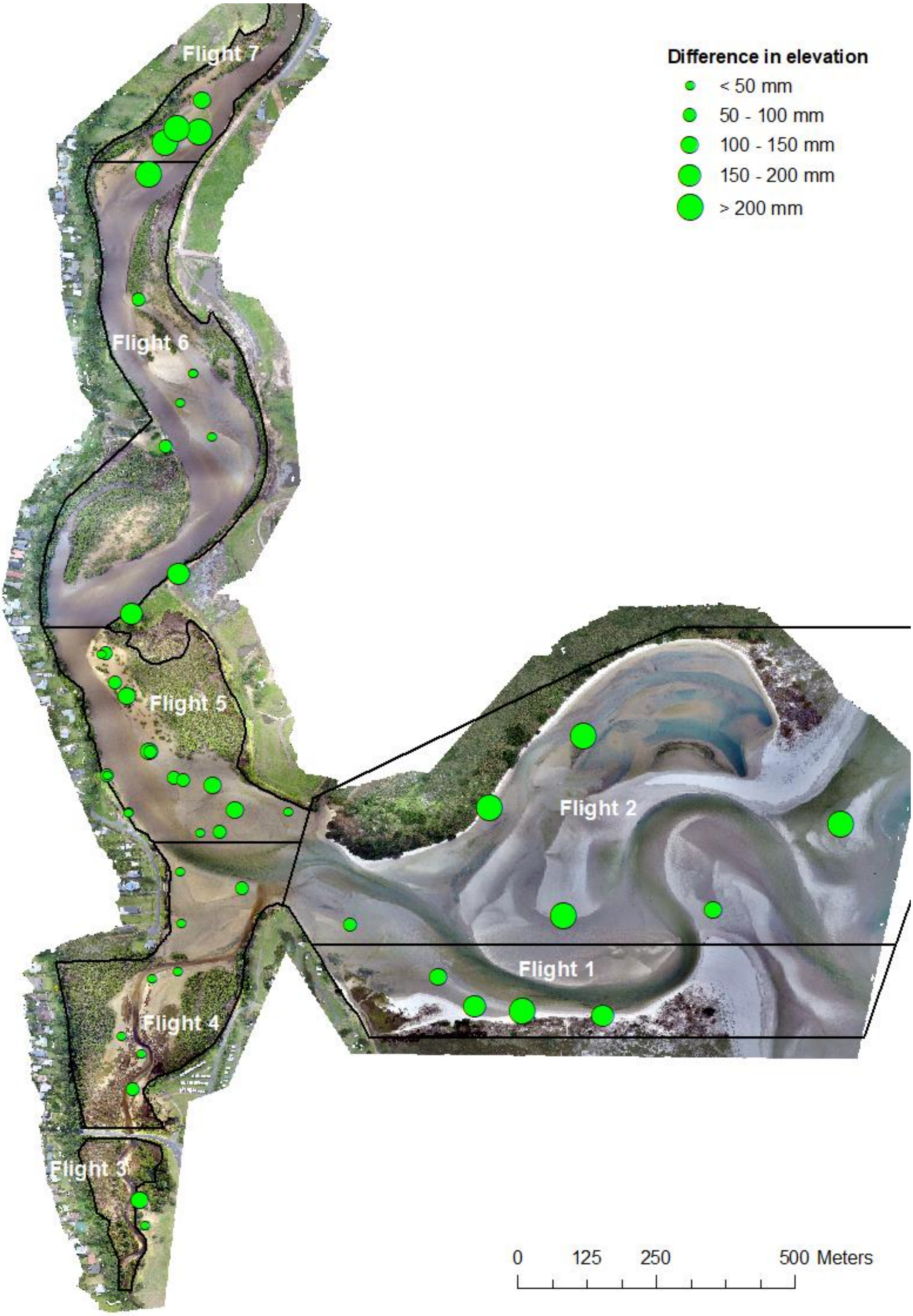

Figure 7. Differences in elevation between RTK GPS surveyed elevation data and DEM derived z values for check points in Ruakaka Estuary.

3.2 Habitat mapping

A total of 998 point features, 62 polygons and 32 line features were recorded in the Collector app and uploaded into ArcMap (Figure 8). The northern section of the main river channel was not surveyed due to difficulties accessing the western bank of the river channel resulting in most of flight zone 7 not being covered by the survey. Several other areas could not be easily accessed and therefore were not surveyed. In particular, an area of saltmarsh habitat behind thick mangrove forest on the eastern bank of the river channel could not be easily accessed. The total area mapped in this study was 460,262m^2. The total area that could not be classified was 6,901m^2, which is about 1.5% of the total surveyed area. A further 6,082m^2 which is about 1.3% of the total surveyed area, was classified as saltmarsh using the orthomosaic GeoTiff but was not surveyed, so was not classified at the level of structural class or dominant cover.

Figure 8. Substrate and habitat features collected in Ruakaka Estuary.

3.2.1 Substrate

As it was not always possible to determine the substrate beneath vegetated areas, the decision was made to only map 'substrate' for un-vegetated areas of the estuary. The total un-vegetated area of intertidal habitat mapped in this study was 331,477.6m^2 (Table 6), which represents 72% of the total surveyed area. A total of 481 point features, 14 polyline features and 18 polylines were collected with substrate information in the survey.

The two dominant substrate classes recorded were firm sand and mobile sand (Table 6 & Figure 9). Together these two categories covered almost 82% of the un-vegetated area surveyed (Table 6). The lagoon section of the estuary comprised mainly mobile sand and firm sand. Soft sand and very soft sand were also recorded in the section of the estuary. No mud substrate was recorded in this section of the estuary. The river channel section of the estuary comprised mainly firm sand at the southern end with more firm sand/mud and soft mud towards the northern reaches of the river channel (Figure 9). The southern spur comprised mainly firm sand, with a small area of soft mud. This small patch was found in an area where mangrove trees have been removed.

Table 6. Substrate classes recorded in Ruakaka Estuary.

Substrate	Area (m^2)	Percentage (%)
Very soft sand	8,027.0	2.4
Soft sand	20,573.7	6.2
Firm sand	134,795.7	40.7
Firm sand/mud	16,263.2	4.9
Mobile sand	135,968.6	41.0
Soft mud	12,060.2	3.6
Very soft mud	3674.9	1.1
Gravel field	114.2	>0.1
Total	331,477.6	

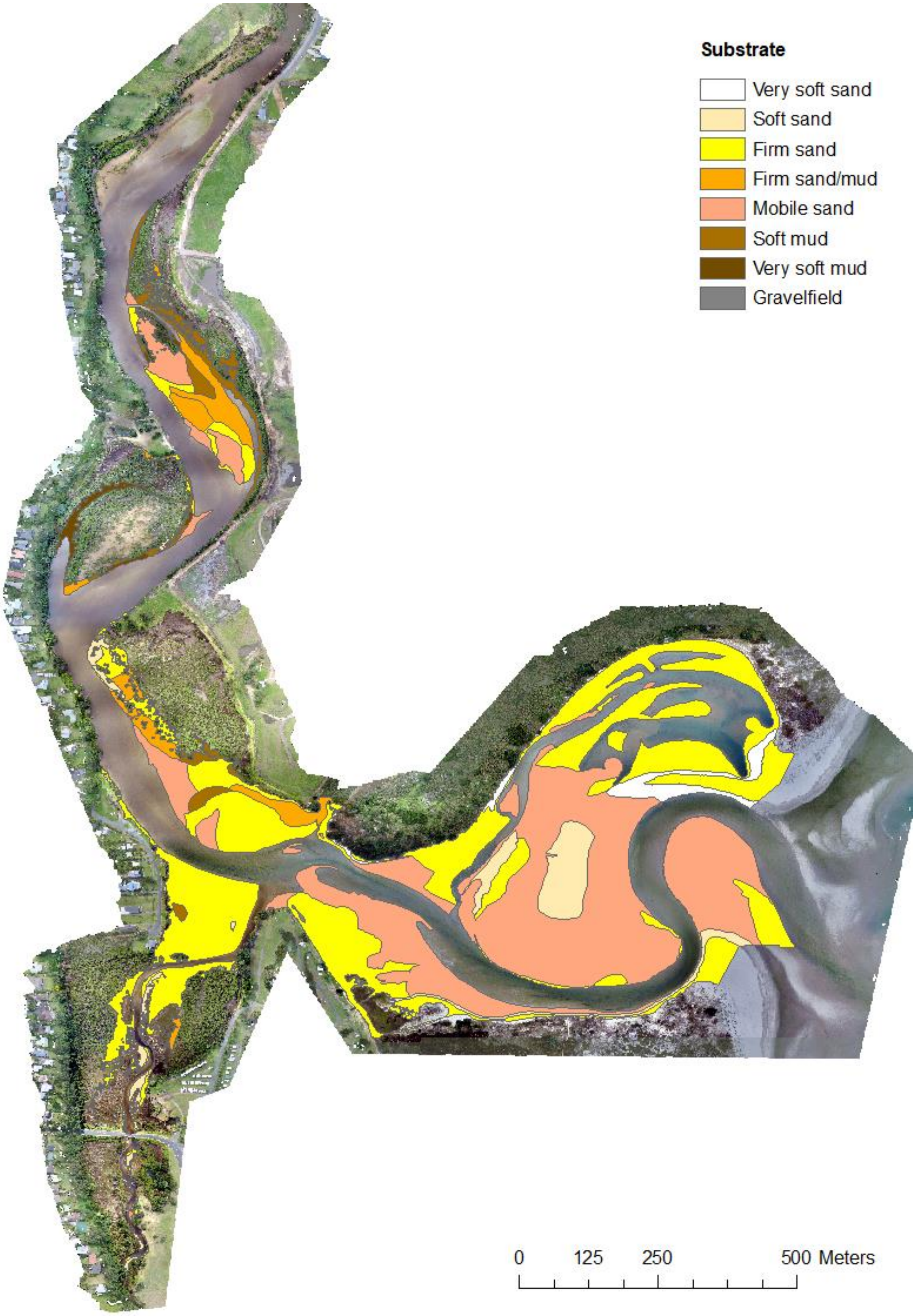

Figure 9. Substrate classes recorded in Ruakaka Estuary.

3.2.2 Fauna

As it was not always possible to determine the flora classification beneath vegetative areas, the decision was made to only map 'fauna' for un-vegetated areas. A total of 481 point features, 7 polyline features and 28 polylines were collected with information about the fauna in the survey. In total, 15 different taxa were recorded (Appendix 4). The only non-native taxa recorded was the pacific oyster *Crassostrea gigas*.

Cockle habitat

Cockles were present at 174 points throughout the estuary. Juvenile cockles were present at 126 points and the threshold for juvenile cockle habitat was reached at 29 points (Figure 10). Juvenile cockle habitat covered an area of 1,152 m^2 but there was some overlap with adult habitat (Figure 10 & 11). Adult cockles were present at 132 sites and the thresholds for adult cockle habitat (low and high density) was reached at 68 points (Figure 11). Adult habitat covered 39,314m^2 (Table 7), which represents approximately 12% of the un-vegetated area surveyed.

High density cockle habitat was mainly found on the larger sand flat at the southern end of the main river channel section of the estuary (Figure 11). Another area of high density habitat was found on sand/mud flats on the eastern bank of the channel further up the river and on the large sand flat at the northern end of the southern spur. In the lagoon, low and high density cockle habitat was found on the southern sand flat, with patches of low density habitat found on the sand flats and sand banks along the northern edge of the lagoon (Figure 11).

Table 7. Cockle habitat in Ruakaka Estuary.

Habitat	Area (m^2)
Juvenile cockle	1,152.2
Low density cockle	19,771.6
High density cockle	19,542.7

Juvenile cockles were almost exclusively found in areas of firm sand (Table 8) and low density cockles were also predominately found in firm sand. High density cockles were predominately found in areas of firm sand but also in mobile sand, firm sand mud and soft mud. The elevation data indicated that juvenile cockles tend to be located at higher elevations than adult cockles. Low density cockles were found at the largest range of elevation, with the mean elevation just above mean sea level (MSL). High density cockle habitat tended to be found at lower elevations with the mean elevation at approximately MSL (Table 8).

Table 8. Elevation data and substrate type for cockle habitat point features collected in Ruakaka Estuary.

Habitat	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Juvenile cockles	29	-0.25	0.42	0.11	Firm sand 97% mobile sand 3%
Low density cockles	43	-0.29	1.82	0.05	Firm sand 77% Mobile sand 9% Firm sand/mud 7%
High density cockles	25	-0.37	0.31	-0.01	Firm sand 52% Firm sand/mud 16% Mobile sand 16% Soft mud 12%

Figure 10. Juvenile cockle habitat in Ruakaka Estuary.

Figure 11. Adult cockle habitat in Ruakaka Estuary.

Pipi habitat

Pipi were recorded at 96 points. Juvenile pipi were present at 52 points and the density threshold for juvenile habitat was reached at 10 points (Figure 12). The mapped juvenile pipi habitat covered 6,156m^2 (Table 9, Figure 12). Adult pipi were present at 64 points and the thresholds for adult pipi habitat (low and high density) were reached at 20 points (Figure 13). The mapped adult pipi habitat covered an area of 8,286m^2, which is approximately 2.5% of the un-vegetated area surveyed (Table 9).

Juvenile pipi habitat was found exclusively in the lagoon section of the bay, in low lying areas adjacent to channels (Figure 12). High density pipi habitat was found exclusively in the lagoon area of the estuary, adjacent to channels (Figure 14). Low density pipi habitat was recorded in the lagoon and on sand flats at the lower end of the southern end of the River channel (Figure 13).

Table 9. Pipi habitat in Ruakaka Estuary.

Habitat	Area (m^2)
Juvenile pipi	6,156.3
Low density pipi	5,123.7
High density pipi	3,162.3

Juvenile pipi was found exclusively on firm sand substrate and low density adult pipi was predominantly found on firm sand (Table 10). High density pipi habitat was found in both firm sand and mobile sand. Juvenile pipi and adult pipi habitat was only recorded at a relatively small number of points (28 points in total) but the data indicates that the mean elevation for both juvenile and adult pipi habitat was below MSL (Table 10).

Table 10. Elevation data and substrate type for pipi habitat point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Juvenile pipi	10	-0.39	0.29	-0.14	Firm sand 100%
Low density pipi	10	-0.30	0.21	-0.07	Firm sand 90% Mobile sand 10%
High density pipi	10	-0.35	0.29	-0.08	Firm sand 50% Mobile sand 50%

Figure 12. Juvenile pipi habitat in Ruakaka Estuary.

Figure 13. Adult pipi habitat in Ruakaka Estuary.

Macomona liliana habitat

Macomona liliana were present at 116 points in the estuary. Juvenile *Macomona liliana* were present at 73 points but the threshold for juvenile habitat was only reached at 11 points (Figure 14). The habitat covered 5,807 m^2 but there was some overlap with adult habitat (Table 11, Figure 14 & 15). Adult *Macomona liliana* were present at 106 points and the density threshold for *Macomona liliana* habitat was only reached at 16 points (Figure 15). The mapped *Macomona liliana* habitat covered an area of 16,335.8m^2 which is about 5% of the un-vegetated area surveyed (Table 11 & Figure 15).

The largest area of juvenile *Macomona liliana* habitat was found on the sand flat at the northern end of the southern spur, with smaller area found on the northern shore of the outer lagoon (Figure 15). Three large adult *Macomona liliana* habitats were found, two on sand mud flats on the eastern side of the main river channel and another on the northern shore of the outer lagoon (Figure 15).

Table 11. *Macomona liliana* habitat in Ruakaka Estuary.

Habitat	Area (m^2)
Juvenile *Macomona liliana*	5,806.7
High density *Macomona liliana*	16,335.8

Juvenile and adult *Macomona liliana* were exclusively found in areas of firm sand (Table 12). The elevation data shows that juvenile *Macomona liliana* habitat was recorded at higher elevations than adult *Macomona liliana* habitat (Table 12). The mean elevation for juvenile *Macomona liliana* habitats was 0.24m above MSL while adult *Macomona liliana* habitat was 0.06m above MSL.

Table 12. Elevation data and substrate type for *Macomona liliana* habitat point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Juvenile *Macomona liliana*	11	0.02	0.35	0.24	Firm sand 100%
Adult *Macomona liliana*	16	-0.26	0.33	0.06	Firm sand 100%

Figure 14. Juvenile *Macomona liliana* habitat in Ruakaka Estuary.

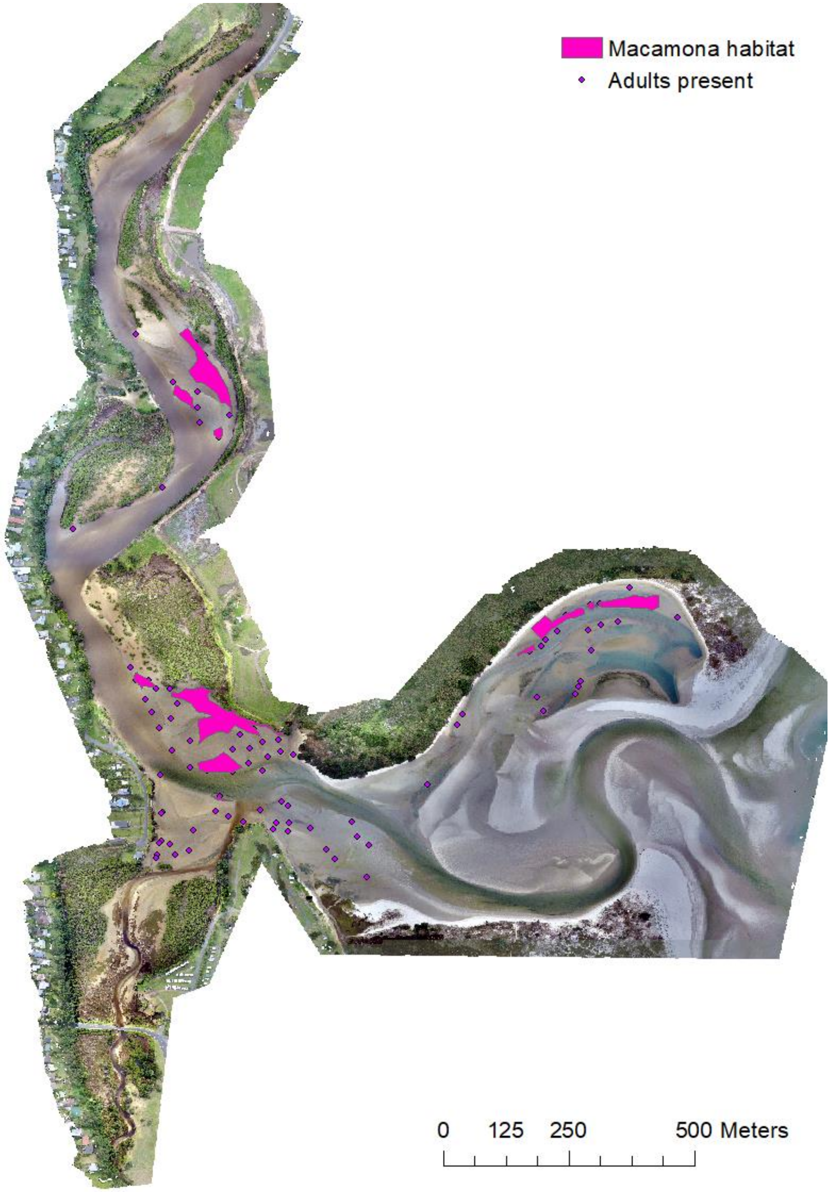

Figure 15. Adult *Macomona liliana* habitat in Ruakaka Estuary.

Crustacean burrows

Crustacean burrows were recorded at 101 sites and covered an area of 36,666.1m^2, which represents 11% of the un-vegetated area surveyed (Figure 16). The actual area of crustacean habitat in Ruakaka Estuary is likely to be much larger as crustacean burrows were regularly recorded at vegetated sites, including areas of rushland, herbfields and mangrove forest, but in this study fauna within saltmarsh or mangrove habitat was not mapped.

The largest areas of crustacean burrows were found adjacent to mangrove and saltmarsh habitat in the main river channel and the southern spur (Figure 16). Relatively large areas were also observed on the sand flats at the northern end of the southern spur and on a sand flat towards the northern end of the river channel. In addition, four smaller areas of crustacean burrows were found in the lagoon section of the estuary (Figure 16).

Figure 16. Crustacean burrow habitat in Ruakaka Estuary.

Crustacean burrows were found in six of the eight substrate classes (Table 13). The only substrates where crustacean burrows were not recorded was gravelfield and very soft sand. Crustacean burrows were recorded mainly on areas of firm sand (61%), firm sand/mud (16%) and soft mud (10%). The elevation data indicates that crustacean burrows were recorded at a wide range of elevations from almost 0.78m below mean sea level to 4.10m above mean sea level (Table 13). The mean elevation was 0.43m above mean sea level.

Table 13. Elevation data and substrate type for crustacean burrows point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Crustacean burrows	101	-0.78	4.10	0.43	Firm sand 61% Firm mud/sand 16% Soft mud 10% Very soft mud 3% Soft sand 3% Mobile sand 2%

Zeacumantus lutulentus

Small pockets of *Zeacumantus lutulentus* were found throughout the estuary and covered an area of 6,034.3m^2, which is approximately 1.8% of the un-vegetated area surveyed (Figure 17). 72% of Zeacumantus *lutulentus* observations were recorded on firm sand, with observations also occurring on firm sand/mud (14%) and soft mud (14%). The elevation data indicated that *Zeacumantus lutulentus* habitat was recorded from 0.17m below mean level to 1.37m above mean sea level (Table 14).

Table 14. Elevation data and substrate type for *Zeacumantus lutulentus* point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Zeacumantus lutulentus	25	-0.17	1.37	0.40	Firm sand 72% Firm sand/mud 14% Soft mud 14%

Diloma subrostratum

Diloma subrostratum covered an area of 3,425.0m^2, which is approximately 1% of the un-vegetated area surveyed. All of the *Diloma subrostratum* habitat mapped in this study was on sand banks in the northern area of the lagoon section of the estuary (Figure 18).

All of the *Diloma subrostratum* habitat observations were recorded on firm sand (Table 15). The elevation data indicated that *Diloma subrostratum* habitat was recorded in a very narrow elevation range (between 0.61m and 0.65m above mean sea level), although there were only nine observation points.

Table 15. Elevation data and substrate type for *Diloma subrostratum* point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Diloma subrostratum	9	0.61	0.67	0.65	Firm sand 100%

Amphibola crenata

Amphibola crenata habitat was recorded at just three locations. All three observations were recorded on firm sand in a very narrow elevation range (between 0.01m and 0.11m above mean sea level) (Table 16).

Table 16. Elevation data and substrate type for *Amphibola crenata* point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Amphibola crenata	3	3	0.11	0.01	Firm sand 100%

Oyster habitat

Only three small areas of oyster habitat were recorded. They were all found in the southern spur sections of the estuary and combined covered an area of 188.8 m^2. All five of the observations were recorded on firm sand in a very narrow elevation range (between 0.28m and 0.39m above mean sea level) (Table 17).

Table 17. Elevation data and substrate type for oyster habitat point features collected in Ruakaka Estuary.

	No. of points	Min elevation (m)	Max elevation (m)	Mean elevation (m)	Substrate
Oyster habitat	5	0.28	0.39	0.33	Firm sand 100%

Figure 17. *Zeacumantus lutulentus* habitat in Ruakaka Estuary.

Figure 18. *Diloma subrostratum* habitat in Ruakaka Estuary.

3.3.3 Flora

The vegetative area mapped in this study covered 128,675m^2 (Table 18). A total of 384 point features, one polyline features and three polygon were collected within vegetative area of the survey. In total, 21 different taxa were recorded. Eight of these were non-native taxa (Appendix 5).

Table 18. Mangrove and saltmarsh habitat in Ruakaka Estuary.

Habitat	Area (m^2)
Saltmarsh	42,524.7
Juvenile Mangroves	4,333.0
Adult Mangroves	81,927.3
Total	128,785.0

Mangroves

The orthomosic GeoTiff was used extensively to map the extent of mangrove habitat in the estuary. Juvenile mangroves covered and area of 4,333.0m^2 and adult mangroves covered a further 81,927.3m^2 (Table 18). Together juvenile and adult mangroves covered approximately 19% of the total area surveyed in this study.

Saltmarsh

Saltmarsh habitat was recorded at 365 points and three polygon features. Saltmarsh habitat covered an area of 42,524.7m^2, which is 9% of the total area surveyed. Rushland was the dominant wetland class (58%), followed by herbfield (24%) and scrub (10%) (Table 19).

The southern spur consisted of a sizeable saltmarsh/mangrove complex (Figure 19, 20, & 21) and three large mangrove saltmarsh habitats were also identified in the main river channel section of the estuary (Figure 22, 23 & 24). Unfortunately, the saltmarsh in the lower portion of this section was not surveyed as it is inaccessible from the estuary (Figure 24). One saltmarsh habitat was mapped on the southern shore of the outer lagoon section (Figure 25). Another saltmarsh complex was identified on the northern shore of the lagoon, but this area was not fully captured by the aerial image and was not surveyed (Figure 26).

Table 19. Wetland classes for saltmarsh habitat in Ruakaka Estuary.

Wetland Class	Polygons	Area (m^2)	Percentage (excluding unclassified)
Herbfield	147	8642.3	23.9
Grassland	16	2649.4	7.3
Rushland	169	20804.9	57.5
Reedland	1	385.9	1.1
Tussockland	5	144.4	0.4
Scrub	35	3538.7	9.8
Other	1	2.0	0.0
Unclassified	13	6357.0	

Figure 19. Mangrove and saltmarsh habitat recorded in Ruakaka Estuary.

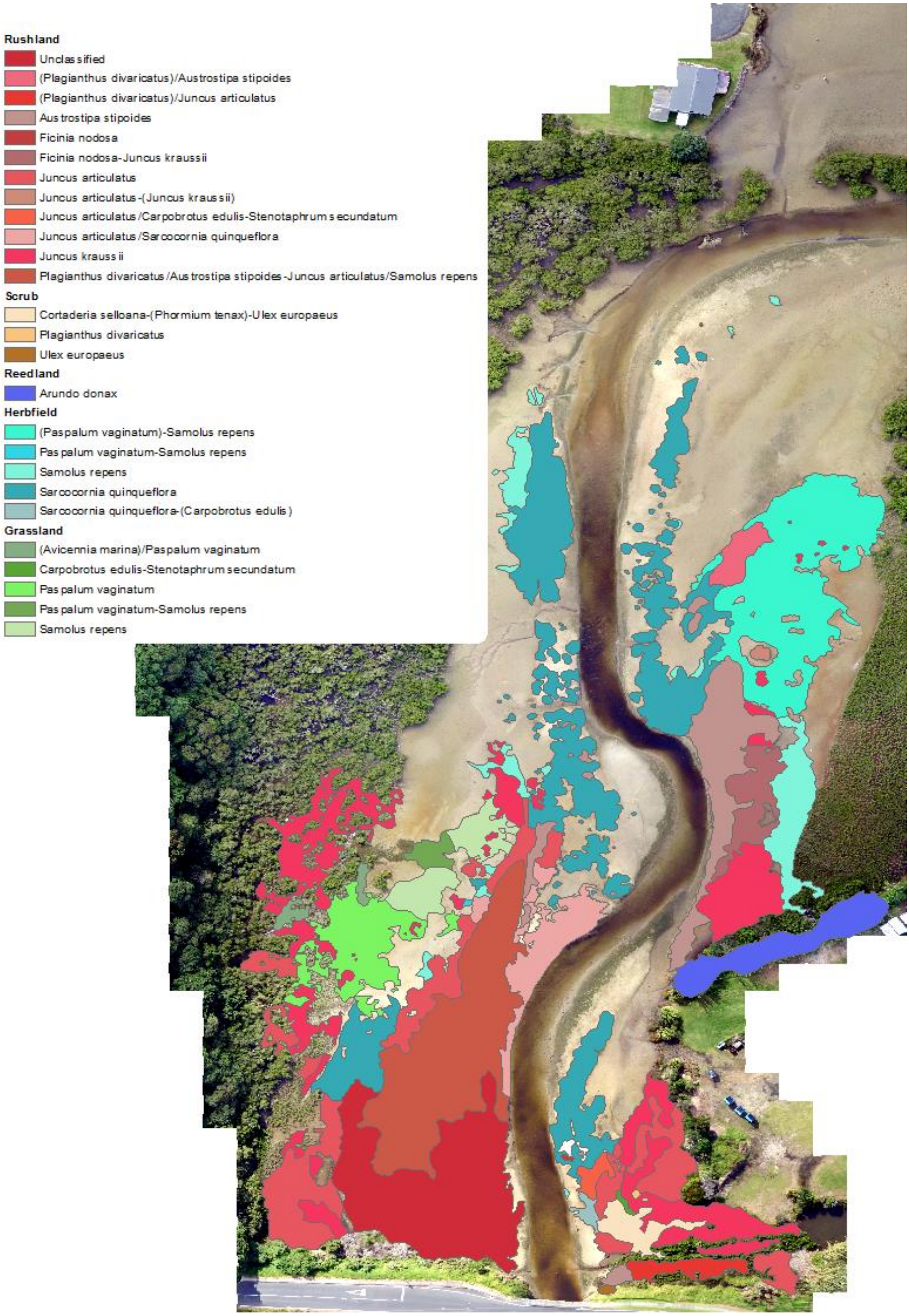

Figure 20. Saltmarsh habitat north of Ruakaka Beach Road in the southern spur.

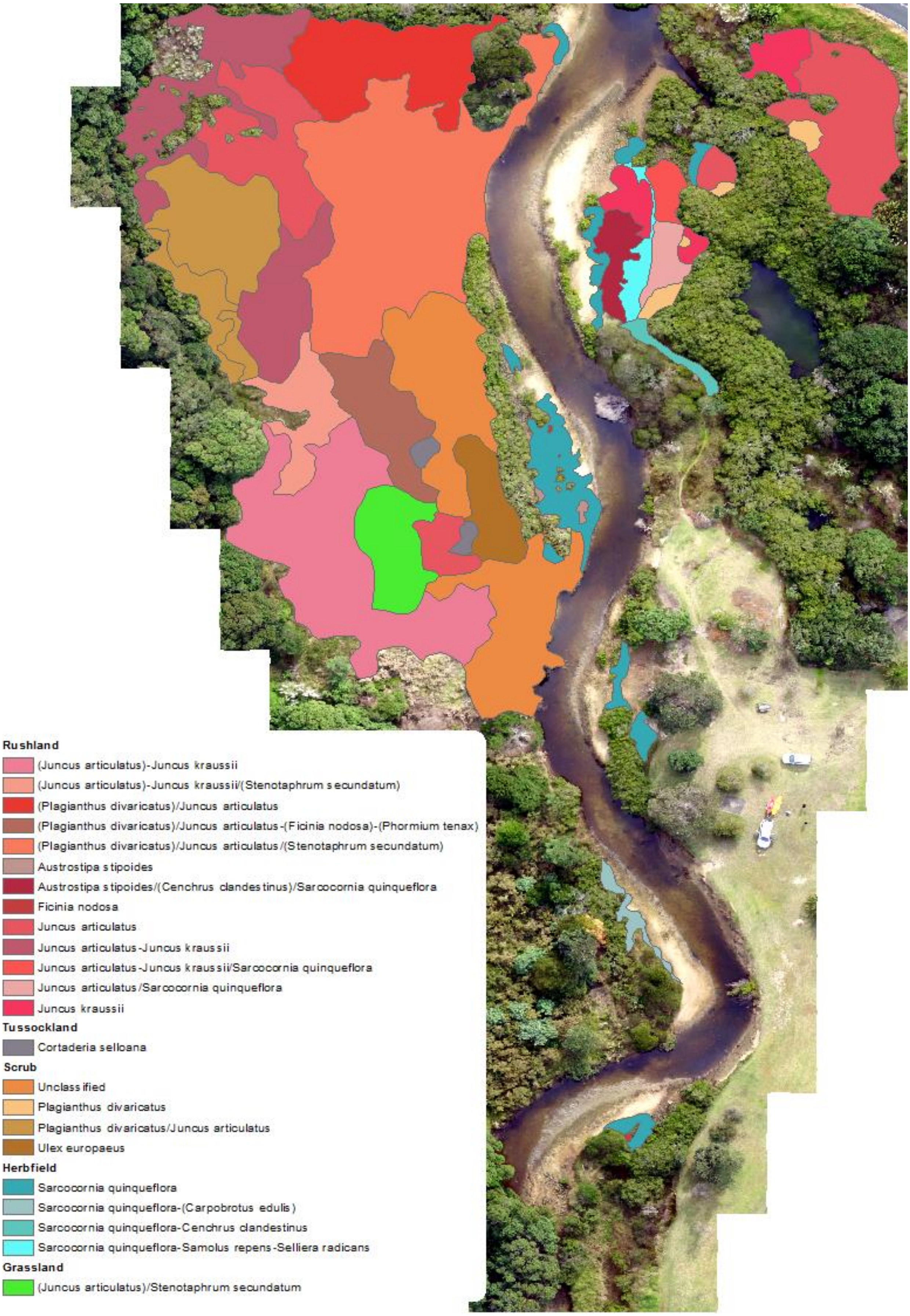

Figure 21. Saltmarsh habitat south of Ruakaka Beach Road in the southern spur.

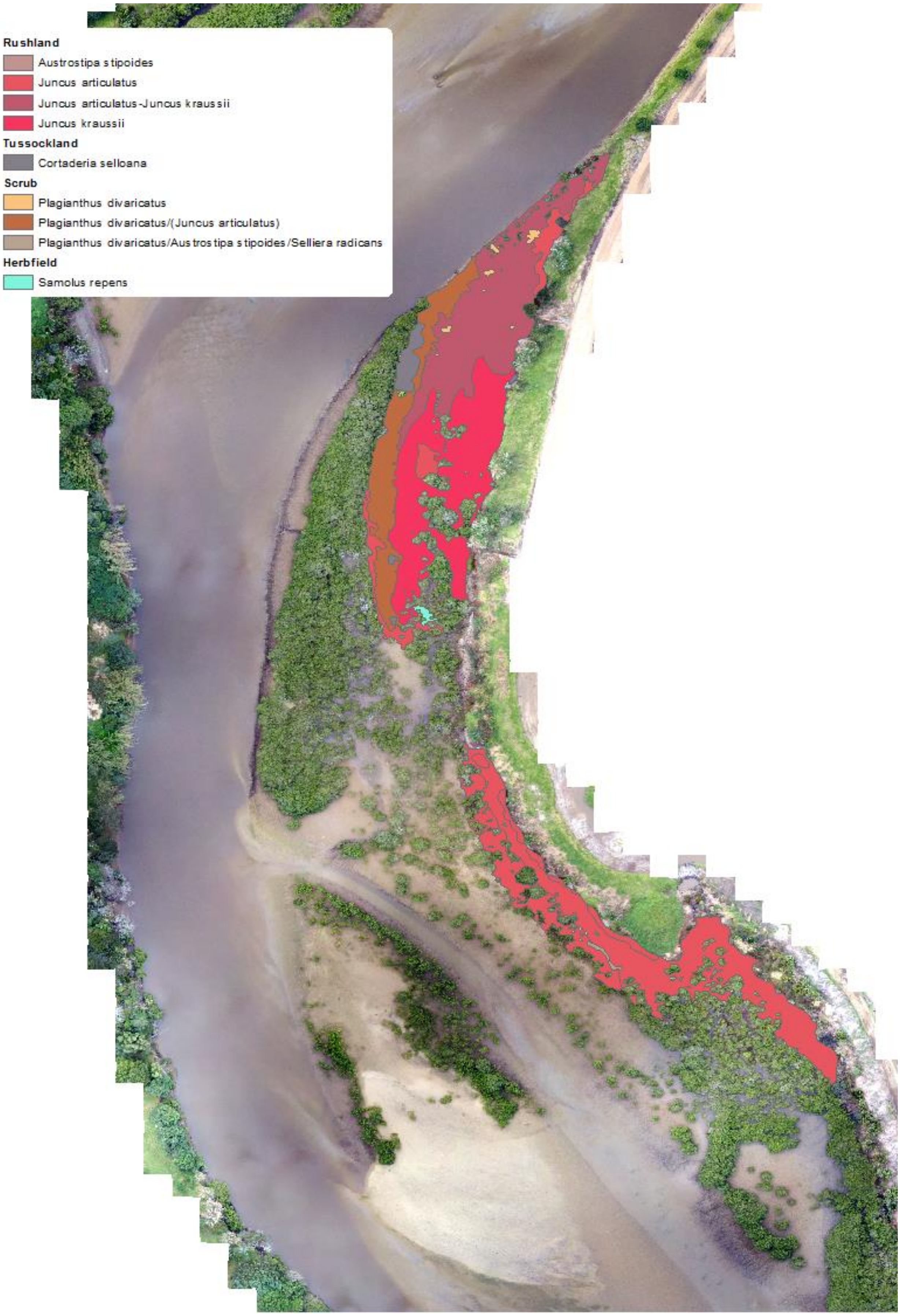

Figure 22. Saltmarsh habitat towards the north of the main river channel.

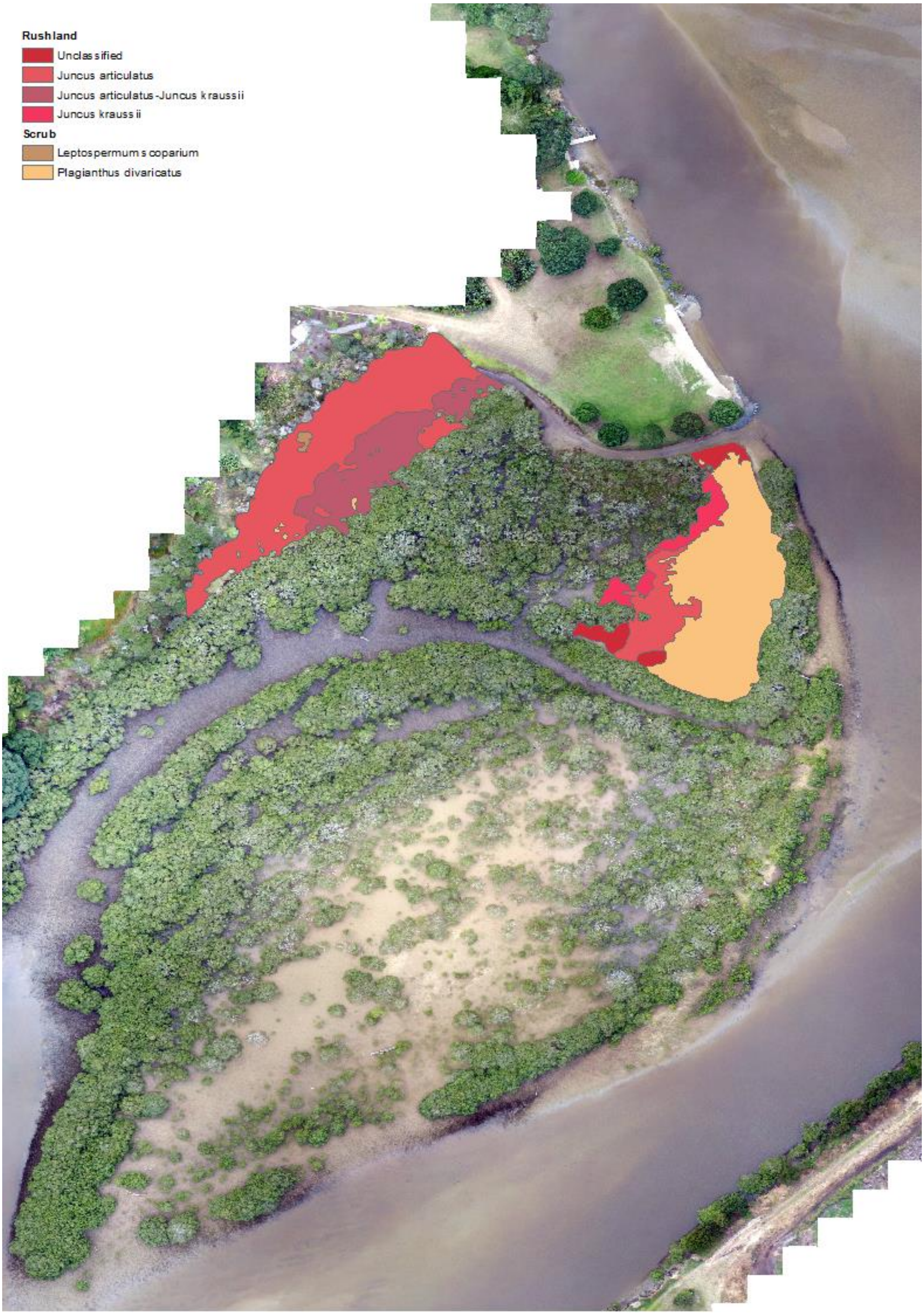

Figure 23. Saltmarsh habitat on the western bank of the main river channel.

Figure 24. Saltmarsh habitat towards the south of the river channel.

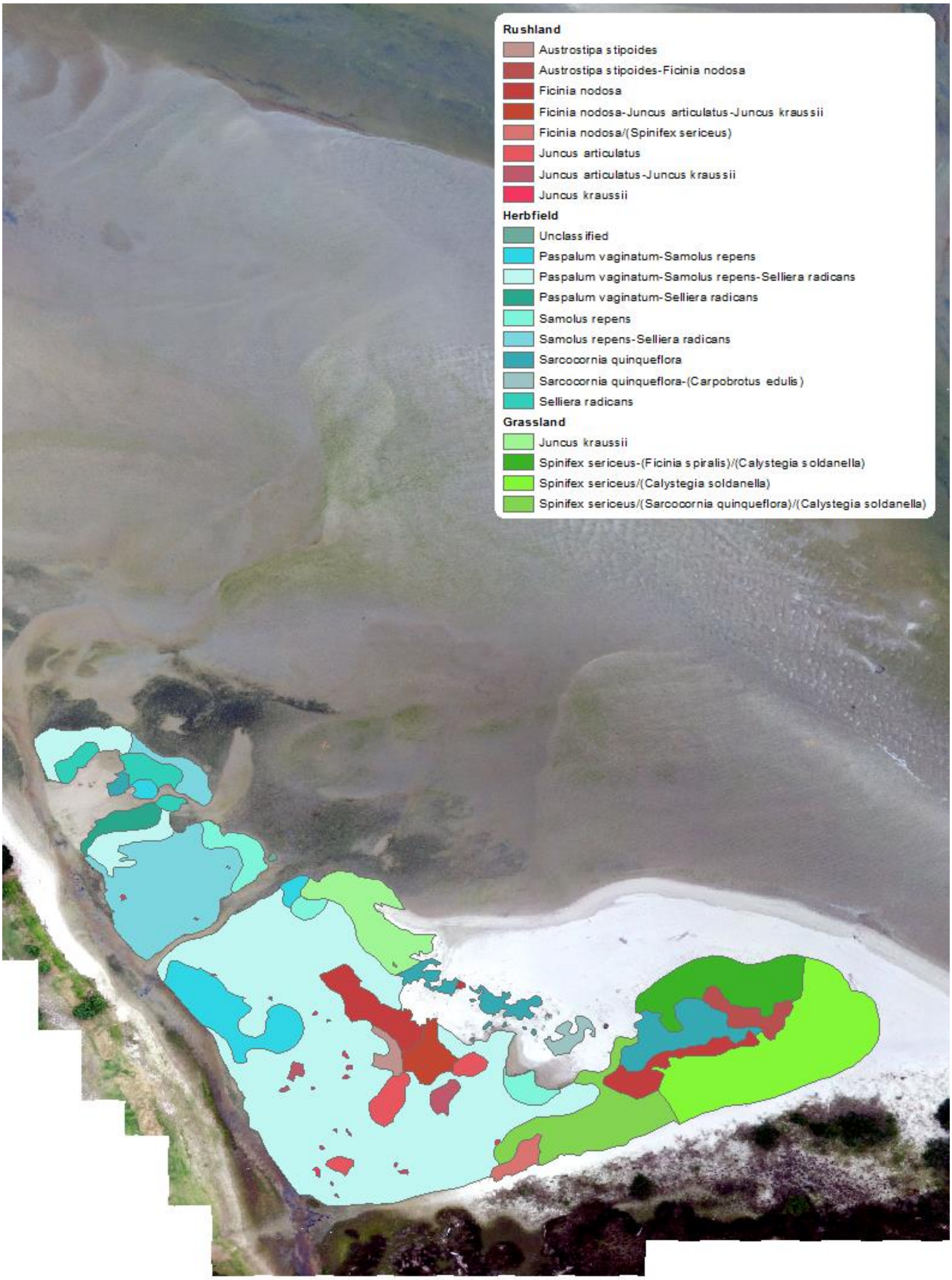

Figure 25. Saltmarsh habitat in the lagoon section of the estuary.

Figure 26. Unmapped saltmarsh habitat on the northern shore of the lagoon section of the estuary.

4 Summary

4.1 Sedimentation

This study investigated the use of RPAS technology and the principles of photogrammetry to collect elevation data at an estuary-wide scale.

The mean horizontal precision of the RTK GPS survey marks was 20.9mm and the mean difference between the DEM z values and the RTK GPS survey marks was 102mm. This suggests that the 'overall' error of the DEM was approximately 121mm. Unfortunately, this is unlikely to be accurate enough to measure sedimentation rates in the short term (5-10 years). Current sedimentation recorded at Council's two sedimentation plates in Ruakaka was 2mm and 5mm per year (between 2009 and 2018). Assuming that the overall accuracy of the DEM achieved in this survey (121mm) could be achieved in a repeat survey, the overall error of the two DEMs is likely to be greater than sedimentation rates in the short term.

It may however be possible to improve the accuracy of a DEM created using a RPAS survey. Due to the shape of the estuary, the weather conditions on the scheduled flight days and the RPAS battery capacity, the estuary had to be flown over multiple days. This is likely to have affected the accuracy of the DEM model. One option may be to divide the estuary into smaller zones and survey and process these smaller areas separately.

Some flight zones of the estuary also had significantly better agreement between the DEM z values and the RTK GPS elevation data than other flight zones. The best agreement was observed in flight zone 4 where the mean difference between z values and RTK survey elevation was 29mm. In this area, the GCPs were well spaced and located away from the edge of the image and water surfaces. In areas where there was poor agreement between the z vales and the RTK survey data, it may have been possible to improve the accuracy of the DEM if GCPs had been better placed. It may be necessary to fly larger areas, beyond the area of interest, so that GCPs can be more easily located 15m from the boundary of the flight area.

As RPAS and camera technology advances, the accuracy of the DEMs may also improve. For example, the camera on the latest Phantom 4 RPAS has a camera with a higher resolution than the Phantom 3 used in the current study. A better resolution camera is likely to improve the accuracy of the DEM. In addition, as battery technology improves it may be possible to fly larger areas in one continuous flight. The use of fixed wing aircraft (RPAS or light aircraft) would allow for a larger area of coverage, however this technology would introduce greater levels of complexity and require professional assistance.

Even, with these improvements it is unlikely to be sufficient to detect sedimentation rate of 2-5mm per year in the short term. Instead, the DEMs could be used to compliment data collected from an array of sediment plates to provide a greater spatial context to the sediment plate data. A possible monitoring framework could involve the installation of sediment plates throughout an estuary. The buried sediment plates and the sediment depth above the plates could be surveyed using an RTK GPS survey or laser scanning. GCPs could be surveyed and an RPAS used to collect aerial images and build a DEM. Measurements of sediment deposition above the sediment plates could then be undertaken at regular frequencies, with physical surveys and RPAS surveys undertaken at 5 or 10 year periods to provide greater spatial context to the sediment plate data.

In addition, surveys of the substrate could be undertaken at 5 or 10 year intervals, either using similar methods to the current study or by collecting sediment samples for sediment grain size analysis. These surveys could be used to determine if the sediment characteristics change over time, i.e. does the estuary, or areas of it, become muddier over time.

Together these techniques (RTK GPS and RPAS surveys, sediment plates and surveys of sediment characteristics) could be used to provide a more holistic understanding of sedimentation patterns within an estuary. This could provide Council with a relatively inexpensive suite of methods to assess, whether the PRP and Council's non regulatory tools (soil conservation) are effective in reducing sedimentation rates in Northland estuaries.

4.2 Habitat mapping

The current study investigated the use of RPAS technology, to facilitate rapid estuary wide ecological surveys. The high quality, contemporary aerial image, obtained by the RPAS, provided significant assistance when mapping areas of saltmarsh and mangrove habitat. It is likely that the image significantly reduced the time required to produce a map of similar quality, using existing conventional aerial images.

The image provided assistance when mapping the substrate type, as the boundaries of some substrate types were clearly apparent from the orthomosaic GeoTiff and complimented the information collected by field staff. The quality of the image obtained was so high that it was possible to identify the footprints from field staff, and this was used to help determine the boundaries between substrate classes (for example between soft sand and firm sand). The elevation outputs from the RPAS survey, and in particular the contour shapefile, also assisted in delimiting the boundaries of substrate classes. Without the orthomosaic GeoTiff and the contour shapefile it would have been necessary to draw arbitrary boundaries for substrate classes between field observations.

The image was of less assistance when mapping the fauna as identifying features like cockle and pipi habitat was more reliant on field observations. However, the substrate boundaries determined with the help of the aerial image and the elevation outputs from the RPAS survey were useful in delimiting the boundaries of different habitats.

Overall, the outputs from the RPAS survey appear to provide a useful suite of outputs for mapping intertidal substrate and indigenous habitats within an estuary. This could help Council to conduct relatively inexpensive assessments of a representative sample of marine SEAs identified in the PRP. Repeat surveys could then be undertaken at 5 or 10 year intervals to assess whether the PRP provisions has been effective at protecting those SEAs.

4.3 Habitat preferences

The present study enabled the identification of the substrate type and elevation at which different habitats were found. In the future, this data could be used to model species distributions. This modelling provides a species' distribution model of environmental suitability in geographic space, which rages form 0 (unsuitable) to 1 (highly suitable), based on a suite of environmental variables included in the modelling (Phillips *et al*., 2006). A model such as this, using for example sediment characteristics and elevation data, could be used to identify areas of high suitability for different taxa or as a surrogate for abundance. This could enable Council to 'map' different habitats of interest, for example shellfish beds, at a region-wide scale more effectively than conducting field surveys.

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Appendices

Appendix 1 Attribute drop downs options created in Collector

Substrate	Flora	Fauna
Very soft mud	Adult mangroves	Juvenile cockles
Soft mud	Juvenile mangroves	Low density cockles
Firm mud/sand	Herbfield	High density cockles
Firm sand	Grassland	Juvenile pipi
Mobile sand	Rushland	Low density pipi
Soft sand	Reedland	High density pipi
Very soft sand	Tussockland	Juvenile *Macomona liliana*
Gravelfield	Scrub	High density *Macomona liliana*
Very soft mud	Other	Oysters
Soft mud	Unclassified	Crustacean burrows
Firm mud/sand	N/A	Mounds and pits
N/A		*Diloma subrostratum*
		Amphibola crenata
		Zeacumantus lutulentus
		Low density
		N/A

Appendix 2 – RTK GPS ground control points

Point ID	Date	Time	Easting	Northing	Elevation	Horizontal precision	Vertical observation	DEM derived z value	Difference between z value and RTK GPS elevation
GCP_3200	17/04/2018	1:39:13 p.m.	371890.9	908505.3	0.334408	0.013461	0.01657	0.369056	0.034648
GCP_3201	17/04/2018	1:42:41 p.m.	371893.5	908414	0.313432	0.016687	0.020467	0.327148	0.013716
GCP_3202	17/04/2018	1:45:33 p.m.	371887.5	908326.5	0.373044	0.016817	0.020156	0.389583	0.016539
GCP_3203	17/04/2018	1:47:12 p.m.	371850.2	908314.5	0.453048	0.017442	0.020718	0.464396	0.011348
GCP_3204	17/04/2018	1:49:34 p.m.	371799.5	908270.5	0.523604	0.028059	0.033654	0.441004	-0.0826
GCP_3205	17/04/2018	1:51:28 p.m.	371805.6	908210.9	0.539003	0.025965	0.031247	0.497196	-0.04181
GCP_3206	17/04/2018	1:53:59 p.m.	371790.9	908136.6	0.668293	0.024728	0.029936	0.623435	-0.04486
GCP_3207	17/04/2018	1:56:03 p.m.	371823.8	908115.3	0.334629	0.017002	0.020047	0.244441	-0.09019
GCP_3208	17/04/2018	1:58:19 p.m.	371834.9	908178	0.407347	0.01663	0.019587	0.392771	-0.01458
GCP_3209	17/04/2018	2:06:16 p.m.	371857.7	908259.3	0.510044	0.014822	0.018157	0.503413	-0.00663
GCP_3210	17/04/2018	2:12:12 p.m.	371941.2	908395.5	0.370205	0.018337	0.023034	0.356751	-0.01345
GCP_3211	17/04/2018	2:15:08 p.m.	371982.4	908475.8	0.22333	0.021401	0.027946	0.152238	-0.07109
GCP_3212	17/04/2018	2:25:01 p.m.	372140.1	908412.4	0.268094	0.017629	0.0249	0.217886	-0.05021
GCP_3213	17/04/2018	2:37:22 p.m.	372182.5	908318.9	0.635634	0.022241	0.033616	0.656631	0.020997
GCP_3214	17/04/2018	2:39:42 p.m.	372269.1	908319.6	0.371351	0.022364	0.035364	0.485279	0.113928
GCP_3215	17/04/2018	2:41:37 p.m.	372322.9	908267.3	0.389261	0.023184	0.037467	0.540916	0.151655
GCP_3216	17/04/2018	2:43:47 p.m.	372391.2	908259	0.349832	0.025285	0.040988	0.627525	0.277693
GCP_3217	17/04/2018	2:47:27 p.m.	372510.5	908251.1	0.521833	0.026787	0.045955	0.694061	0.172228
GCP_3218	17/04/2018	2:50:41 p.m.	372657.5	908341.1	1.185958	0.025233	0.042266	1.237646	0.051688
GCP_3219	17/04/2018	2:53:35 p.m.	372789.5	908263	0.079584	0.026884	0.046321	0.114703	0.035119
GCP_3220	17/04/2018	3:00:22 p.m.	372670.3	908441.1	0.301791	0.024167	0.040254	0.435377	0.133586
GCP_3221	17/04/2018	3:03:36 p.m.	372649	908547.7	0.030069	0.035253	0.061406	0.023997	-0.00607
GCP_3222	17/04/2018	3:14:46 p.m.	372823.4	908475	0.019539	0.021794	0.037083	-0.039259	-0.0588
GCP_3223	17/04/2018	3:17:57 p.m.	372855.1	908595.6	0.307218	0.022739	0.038672	0.071505	-0.23571
GCP_3225	17/04/2018	3:37:07 p.m.	372756.2	908628.8	1.20679	0.027354	0.041032	1.078816	-0.12797
GCP_3226	17/04/2018	3:43:08 p.m.	372628.7	908919.1	0.587894	0.025347	0.037269	0.700658	0.112764
GCP_3227	17/04/2018	3:47:22 p.m.	372480	908752.2	0.243702	0.021844	0.031924	0.021443	-0.22226
GCP_3228	17/04/2018	3:51:35 p.m.	372342.9	908624.3	0.67641	0.022452	0.032125	0.376613	-0.2998
GCP_3229	17/04/2018	3:57:22 p.m.	372450.7	908429.5	0.602284	0.017817	0.024826	0.818709	0.216425
GCP_4000	27/04/2018	11:25:31 a.m.	371826.9	907813	0.588717	0.013962	0.019856	0.807981	0.219264
GCP_4001	27/04/2018	11:28:32 a.m.	371840.8	907870.8	1.396661	0.018285	0.025919	1.429212	0.032551
GCP_4002	27/04/2018	11:30:27 a.m.	371833.7	907916.6	1.032041	0.01798	0.024592	1.137332	0.105291
GCP_4003	27/04/2018	11:32:55 a.m.	371815.2	907991.2	0.532429	0.016496	0.023166	0.461832	-0.0706
GCP_4004	27/04/2018	11:35:19 a.m.	371810.5	907949.4	0.6526	0.016482	0.022886	0.759785	0.107185
GCP_4005	27/04/2018	11:46:04 a.m.	371920.4	908576.3	0.107362	0.016904	0.022197	0.145443	0.038081
GCP_4006	27/04/2018	11:48:59 a.m.	372047.9	908614.5	-0.02514	0.016448	0.022191	-0.043777	-0.01864
GCP_4007	27/04/2018	11:52:26 a.m.	371895.7	908670.6	0.230017	0.016194	0.021724	0.305956	0.075939
GCP_4008	27/04/2018	11:54:23 a.m.	371847.4	908722	0.114428	0.016141	0.021609	0.209073	0.094645
GCP_4009	27/04/2018	11:57:41 a.m.	371813.3	908822.2	0.433378	0.016218	0.021574	0.546879	0.113501
GCP_4010	27/04/2018	12:00:03 p.m.	371774.1	908897.3	0.49302	0.016184	0.021038	0.527936	0.034916
GCP_4011	27/04/2018	12:05:57 p.m.	371784.6	908678.5	-0.01446	0.01938	0.028758	-0.029255	-0.0148
GCP_4012	27/04/2018	12:08:05 p.m.	371815.5	908614.6	-0.04375	0.017485	0.022963	-0.021016	0.022734
GCP_5000	1/05/2018	1:45:00 p.m.	371815.2	908611.7	0.060656	0.024774	0.035741	0.059516	-0.00114
GCP_5001	1/05/2018	1:52:46 p.m.	371882.1	908675.4	0.216986	0.013875	0.020831	0.312663	0.095677
GCP_5002	1/05/2018	1:54:26 p.m.	371938.1	908661.7	0.09877	0.017105	0.02586	0.232623	0.133853
GCP_5003	1/05/2018	1:58:54 p.m.	371971.4	908617.4	0.179247	0.029597	0.045123	0.300066	0.120819
GCP_5004	1/05/2018	2:01:12 p.m.	372053.3	908614.4	0.010205	0.028907	0.045433	0.002532	-0.00767
GCP_5005	1/05/2018	2:03:40 p.m.	371949.5	908578.4	0.139906	0.019975	0.032097	0.223052	0.083146
GCP_5006	1/05/2018	2:05:27 p.m.	371905.7	908602.4	0.071339	0.014382	0.02354	0.193897	0.122558
GCP_5007	1/05/2018	2:09:19 p.m.	371846.1	908724	0.097899	0.014162	0.022569	0.227614	0.129715
GCP_5008	1/05/2018	2:13:25 p.m.	371795.9	908845.9	0.414243	0.017563	0.028277	0.50584	0.091597

Point ID	Date	Time	Easting	Northing	Elevation	Horizontal precision	Vertical observati on	DEM derived z value	Difference between z value and RTK GPS elevation
GCP_5009	1/05/2018	2:15:40 p.m.	371781.9	908898.4	0.519773	0.019844	0.035324	0.587247	0.067474
GCP_5010	1/05/2018	2:34:37 p.m.	371818.3	908971.3	1.335923	0.030317	0.047115	1.507296	0.171373
GCP_5012	1/05/2018	2:54:13 p.m.	371887.2	909042.1	1.976585	0.01662	0.0249	2.148855	0.17227
GCP_5028	1/05/2018	4:55:10 p.m.	371914.3	909835.9	0.038646	0.040441	0.051027	0.300373	0.261727
GCP_5027	1/05/2018	4:52:40 p.m.	371919.4	909893	0.191037	0.030008	0.041237	0.336003	0.144966
GCP_5025	1/05/2018	4:44:32 p.m.	371863.7	909817.5	0.08406	0.028106	0.036338	0.321836	0.237776
GCP_5018	1/05/2018	3:53:36 p.m.	371827.9	909533.8	0.265702	0.017196	0.021913	0.320003	0.054301
GCP_5024	1/05/2018	4:42:18 p.m.	371841.3	909759.8	-0.06407	0.026061	0.033761	0.145664	0.209737
GCP_5017	1/05/2018	3:50:16 p.m.	371861.3	909426.7	0.656529	0.02389	0.030061	0.625458	-0.03107
GCP_5019	1/05/2018	3:58:45 p.m.	371906.7	909400.7	0.394991	0.021166	0.026867	0.400644	0.005653
GCP_5020	1/05/2018	4:18:39 p.m.	371868.1	909269.7	1.599164	0.017154	0.021903	1.509904	-0.08926
GCP_5021	1/05/2018	4:23:08 p.m.	371903.1	909130.2	-0.03112	0.014935	0.019148	0.020752	0.051873
GCP_5022	1/05/2018	4:29:27 p.m.	371906.7	909400.7	0.388017	0.018881	0.023957	0.400607	0.01259
GCP_5023	1/05/2018	4:40:10 p.m.	371784.4	909742.9	0.426421	0.022075	0.03019	0.481736	0.055315
GCP_5016	1/05/2018	3:47:40 p.m.	371888.6	909348.9	0.245161	0.024849	0.031401	0.199135	-0.04603
GCP_5013	1/05/2018	3:22:16 p.m.	371784	908678.4	0.10628	0.019844	0.028391	0.028792	-0.07749
GCP_5026	1/05/2018	4:46:01 p.m.	371881.1	909843.5	0.176754	0.027903	0.035716	0.391572	0.214818
GCP_5015	1/05/2018	3:44:47 p.m.	371934.9	909287.3	0.200819	0.011193	0.013376	0.155995	-0.04482
GCP_5014	1/05/2018	3:41:57 p.m.	371981.7	909238.2	0.005997	0.018459	0.023874	0.003046	-0.00295

Appendix 3 Ground control points

Label	X Error (cm)	Y Error (cm)	Z Error (cm)
GCP-3204	-5.4837	-1.0206	0.8065
GCP-3206	1.0918	1.495	0.2212
GCP-3209	0.5738	-1.9656	-2.7174
GCP-3210	0.2209	-1.5308	2.2674
GCP-3213	-2.8115	-0.221	0.3312
GCP-3218	6.3563	-0.8108	3.2796
GCP-3219	-7.3316	2.0214	0.5338
GCP-3221	-0.7119	3.8464	1.2574
GCP-3222	3.094	2.6439	0.6319
GCP-3225	1.3628	-4.0763	-5.0999
GCP-3226	0.5443	-1.8349	3.3555
GCP-4000	-0.0683	-0.3148	-1.0804
GCP-4003	3.719	0.6763	3.997
GCP-4004	-1.6198	0.8108	-1.167
GCP-5004	-0.4119	-1.702	-2.2046
GCP-5006	0.5179	2.2571	2.5394
GCP-5011	-1.5829	-1.1302	-4.112
GCP-5017	-0.3013	-2.6221	-0.3281
GCP-5021	1.5918	3.4414	1.1132
GCP-5023	-0.3008	0.7659	0.1669
GCP-5014	1.0697	-0.9282	-0.8898
Total (RMSE)	2.8385	2.0318	2.3147

Appendix 4 – Fauna recorded in Ruakaka Estuary

Taxa	Common name
Austrovenus stutchburyi	Tuaki/Tuangi, cockle
Paphies australis	Pipi
Macomona liliana	Hanikura, wedge shell,
Paphies subtriangulata	Tuatara
Fellaster zelandiae	Kina Papa, sand dollar
Diloma subrostratum	Whētiko, top shell
Amphibola crenata	Tītiko, mud snail
Austrominius modestus	Werewere, estuarine barnacle
Zeacumantus lutulentus	Koeti, horn shell, spire shell
Chiton glaucus	Papatua Kakāriki, chiton
Cominella glandiformis	Mud flat whelk
Anthopleura aureoradiata	Humenga, mud flat anemone
Crassostrea gigas	Pacific oyster
Unidentified worm	Unidentified worm
Unidentified decapod	Unidentified crab

Appendix 5 - Flora recorded in Ruakaka Estuary.

Structural class	Taxa	Common name
Herbfield	*Sarcocornia quinqueflora*	Glasswort
Herbfield	*Samolus repens*	Sea primrose
Herbfield	*Selliera radicans*	Remuremu
Grassland	*Paspalum vaginatum**	Saltwater paspalum
Grassland	*Stenotaphrum secundatum **	Buffalo grass
Grassland	*Cenchrus clandestinus**	Kikuyu grass
Grassland	*Spinifex sericeus*	Kowhangatara
Grassland	*Ficinia spiralis*	Pingau
Reedland	*Arundo donax**	Giant reed
Rushland	*Juncus kraussii*	Sea rush
Rushland	*Juncus articulatus*	Jointed rush
Rushland	*Austrostipa stipoides*	Coastal immorality grass
Rushland	*Ficinia nodosa*	Wiwi, knobby club rush,
Scrub	*Avicennia marina*	Manawa, mangrove
Scrub	*Plagianthus divaricatus*	Saltmarsh ribbonwood
Scrub	*Ulex europaeus**	Gorse
Tussockland	*Cortaderia selloana**	Pampas grass
Tussockland	*Phormium tenax*	Harakeke, flax
Other	*Carpobrotus edulis**	Ice plant
Other	*Calystegia soldanella*	Nihinihi, shore bindweed
Other	*Senecio elegans**	Purple groundsel

* denotes non-native taxa.

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