Taihoro Nukurangi

Waituna Lagoon level impacts on land drainage and inundation

Investigation stages 1 and 2

Prepared for Department of Conservation

February 2016

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NIWA CLIENT REPORT No: CHC2016-010
Report date: February 2016 (Revised May 2017)
NIWA Project: DOC16501

Quality Assurance Statement		
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Executive summary

Water tables and inundation within parts of the Waituna Lagoon catchment are influenced by water levels within the lagoon, but the extent of this effect is not fully understood. Better understanding of the area of land impacted by different lagoon levels will enable more robust decision making regarding lagoon level regimes. Mapping the area of land impacted by lagoon levels will also identify those areas most vulnerable to inundation or compromised drainage.

To inform decision making in regard to lagoon openings, the Department of Conservation commissioned NIWA, under the Arawai Kākāriki wetland restoration programme, to undertake a two-stage study to map the spatial extent of inundated land for a range of lagoon levels and to predict areas of drainage affected land. This work has been funded from Living Water, a Department of Conservation/Fonterra partnership committed to best practice management of New Zealand's waterways.

Stage 1 of the study was commissioned in September 2015, and involved simple 'bathtub' modelling of the Waituna Lagoon to provide a simple 'first-cut' mapping of the extent of farmland inundated under different lagoon levels, assuming static horizontal water levels. This work was completed in September 2015.

Stage 2 was commissioned in November 2015. This involved a hydraulic model study of the creeks feeding into the Waituna Lagoon with the aim of providing a more accurate mapping of inundated or drainage affected farmland, by including simulated backwater effects. Stage 2 was completed for Waituna and Carran Creeks in February 2016, and for Moffat Creek in May 2017.

This report documents work done and provides results for both stages.

The 'first-cut' maps of inundation extent that have been derived from the simple bathtub modelling have been included. These maps, which show inundation extent under static lagoon water levels, are useful in that they provide inundation extents around the shoreline of the lagoon. However, since they do not allow for hydraulic effects (i.e., steady-flow water level and backwater effects) they cannot be used to assess inundation extents along the main tributary channels resulting from stream flow.

In Stage 2, one-dimensional hydraulic models of Waituna Creek, Carran Creek and Moffat Creek were constructed and calibrated. The models were used to assess water levels in each creek for two flow and two plant abundance scenarios. This modelling has allowed maps of inundation extent and drainage affected farmland to be produced that incorporate steady-state hydraulic effects.

Key results for Waituna Creek:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent up Waituna Creek was to around 400 m upstream of White Pine Road.
- Farmland inundated by high lagoon water levels or backwater effects from Waituna Lagoon is mainly within an area on the true left of the channel south of a farm access road off Marshall Road, about 1 km south of White Pine Road. Significant inundation of this area occurs even at low lagoon levels when the Waituna Creek channel has high plant abundance, indicating that the inundation is related to restriction of the channel rather than the lagoon level.

- At the 90 percentile high flow, the area of land where drainage is potentially affected is much more influenced by plant growth than by lagoon water level (including backwater effects). At mean flow, the lagoon water level has a more significant effect, but with more limited up-channel extent.

Key results for Carran Creek:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was to 1.1 km upstream of Waituna Lagoon Road Bridge.
- The main area of land inundated by high Waituna lagoon levels is west to north-west of Little Lake Waituna. For the scenarios considered, no significant inundation occurred east of Waituna Lagoon Road or north of Hanson Road.
- A 500 m wide swath of land downstream of Waituna Lagoon Road Bridge and west of Waituna Lagoon Road is potentially drainage affected even at low lagoon level (taken as 0.5 m), although much of this land is wetland habitat, not farmland
- At mean flow, except at high lagoon levels (WL > 2.0 m), very little farmland upstream of Waituna Road Bridge is potentially drainage affected, when the river channel is clear of plant growth. If the channel has instead high plant abundance then, more farmland is potentially drainage affected.
- At the 90 percentile high flow, a fairly large area of farmland (~44 ha), upstream of Waituna Lagoon Road Bridge, is potentially drainage affected when the channel is vegetated (under all lagoon levels). This area reduces in size by about 40% if the channel is cleared.

Key results for Moffat Creek:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was about 940 m downstream of Moffat Road Bridge.
- The main area of land inundated by high Waituna lagoon levels is wetland habitat, not farmland. No significant inundation of farmland is predicted.

Overall the area of land inundated by static lagoon water levels up to 2.5 m is relatively minor and generally around the mouths of the three main tributary creeks. For Waituna, Moffat and Carran Creeks the area of land affected by direct inundation and impeded drainage is a function of lagoon level, flow rate and plant growth in the creeks. The relative importance of these three factors varies spatially. The most downstream parts of the Creeks strongly affected by lagoon level but further upstream this has little or no effect and channel vegetation and flow dominate. For high flow, densely vegetated conditions, the lagoon level has less impact as Creek levels are already high. Under high flow conditions the area of farmland with potentially affected drainage is much higher as a result of a vegetated channel than as a result of a high lagoon level (for all three creeks).

While this study provides a good basis for understanding how lagoon levels impact farmland around Waituna Lagoon uncertainty could be reduced by investigating the typical depth of field drains, and conducting further water level and flow surveys in the backwater reaches under different flow and vegetation conditions.

1 Introduction

Water levels within Waituna Lagoon are influenced by lagoon inflows, losses (seepage and evaporation), openings to the ocean, and (when open) tides. The current opening regime involves opening the lagoon once the level exceeds 2 m above mean sea level. The consent which permits this opening regime to occur is up for renewal, and the potential for more flexibility with regard to openings to promote environmental benefits is being considered (for example openings at lower levels to relieve periods of prolonged algal blooms or reducing the frequency of spring/summer openings when this could be beneficial to macrophytes).

Water tables and inundation within parts of the Waituna Lagoon catchment are influenced by water levels within the lagoon, but the extent of this effect is not fully understood. Better understanding the area of land impacted by different lagoon levels will enable more robust decision making regarding lagoon level regimes. Identifying the areas most vulnerable to inundation or compromised drainage will also be useful for management.

To inform decision making in regard to lagoon openings, the Department of Conservation commissioned NIWA, under the Arawai Kākāriki wetland restoration programme, to undertake a two stage study to map the spatial extent of inundated land for a range of lagoon levels and to map drainage affected land. This work has been funded from Living Water, a Department of Conservation/Fonterra partnership committed to best practice management of New Zealand's waterways.

Stage 1 of this study, to undertake simple 'bathtub' modelling of the Waituna Lagoon, was commissioned in September 2015. This was a preliminary study, the aim of which was to provide a simple 'first-cut' mapping of the extent of farmland inundated under different lagoon levels, assuming static horizontal water levels. This work was completed in September 2015.

In December 2015, a second stage of work was commissioned (Stage 2) involving a hydraulic model study of the creeks feeding into the Waituna Lagoon. The Stage 2 study aimed to provide accuracy, by including simulated backwater effects on the creeks and mapping land which was inundated as well as land which was within 1 m of the creek water elevation and hence likely to have its drainage affected. This work was completed for Waituna and Carran Creeks in February 2016.

In October 2016 the study was extended to consider a deeper (2 m) drainage depth as it was felt that many field drains were deeper than 1 m.

In May 2017 the study was extended to include Moffat Creek, which had not been included originally due to difficulties accessing the Creek for cross-section survey.

This report has been updated to include all the work done and provides results for both Stage 1 and Stage 2 of the study.

2 Scope of the project

2.1 Stage 1: Simple 'bathtub' modelling

The scope of work for Stage 1 consisted of building a digital elevation model of the Waituna Lagoon and its surrounding area by combining data from aerial LiDAR and a bathymetry survey of the lagoon, then mapping the extent of farmland inundated under different lagoon levels. Static horizontal water levels are assumed.

The following outputs were required:

- a digital elevation model (DEM) of the lagoon and its catchment;
- maps of inundation extent for a range of static lagoon level scenarios.

2.2 Stage 2: Hydraulic Modelling

The aim of Stage 2 was to refine the analysis of inundation extents to include backwater effects along the main creeks draining into Waituna Lagoon (i.e., Waituna Creek, Moffatt Creek and Carran Creek), through steady-state hydraulic modelling of these creeks.

Tasks required to be carried out by NIWA under Stage 2 were as follows:

1. build a one-dimensional hydraulic model of each of the 3 main creeks using cross-section survey data, from a survey commissioned in December 2015;
2. calibrate the models hydraulically, to match surveyed water levels;
3. perform model runs in each creek for two flows (mean flow and a higher flow) and for a range of lagoon levels.

Outputs required included:

- 1D hydrodynamic models of the main creeks;
- a report providing a technical description of the models, their calibration, and providing information on backwater extents including maps of ground freeboard relative to lagoon water/creek water level for a range of scenarios taking into account backwater effects in the creeks.

TrueSouth Survey Services Ltd were commissioned by the Department of Conservation to undertake the cross-section survey of Waituna Creek, and Carran Creek in December 2015, and Moffat Creek in March 2017. TrueSouth surveyed 7 cross-sections in Carran Creek, 8 cross-sections in Waituna Creek, and 9 cross-sections in Moffat Creek.

3 Stage 1: Simple bathtub modelling

3.1 Methodology

The simple bathtub modelling required a digital elevation model of the Waituna Lagoon and the surrounding area to be constructed. Once constructed this model was used to obtain maps of inundated areas for static lagoon levels.

The following data sources were used to create the DEM:

- a LiDAR point cloud collected between 20-22 March 2012 by NZ Aerial Mapping for Environment Southland;
- bathymetric soundings collected in December 2011 by TrueSouth Survey Services Ltd;
- bathymetric soundings 'Charlie_Bay_Transect_1.shp', provided by Environment Southland.

The LiDAR points were interpolated into raster grids at various resolutions (2 m, 5 m, 10 m, 20 m, and 30 m). The final 'dry land' DEM from LiDAR was then generated by layering these interpolated DEMs with priority given to higher resolutions. Using this method, data gaps in higher resolution DEMs (mainly in the wetlands surrounding the lagoon) were filled with real data interpolated at lower resolutions.

The lagoon bathymetry was interpolated by using the two sets of sounding points as well as LiDAR returns within a 5m distance from the water's edge to assure a smooth transition between lagoon and land elevations.

The final DEM was generated by overlaying the bathymetric raster over the dry land DEM. Technical details of the final version supplied are as follows:

Filename: Waituna_2m_Combined_DEM_filtered.tif
Coordinates: NZTM
Vertical Datum: Bluff 1955
Resolution: 2 m

Figure 3-1 provides an overview of the data sources used. Note, the displayed cross-sections were not used in the DEM and are shown for reference only.

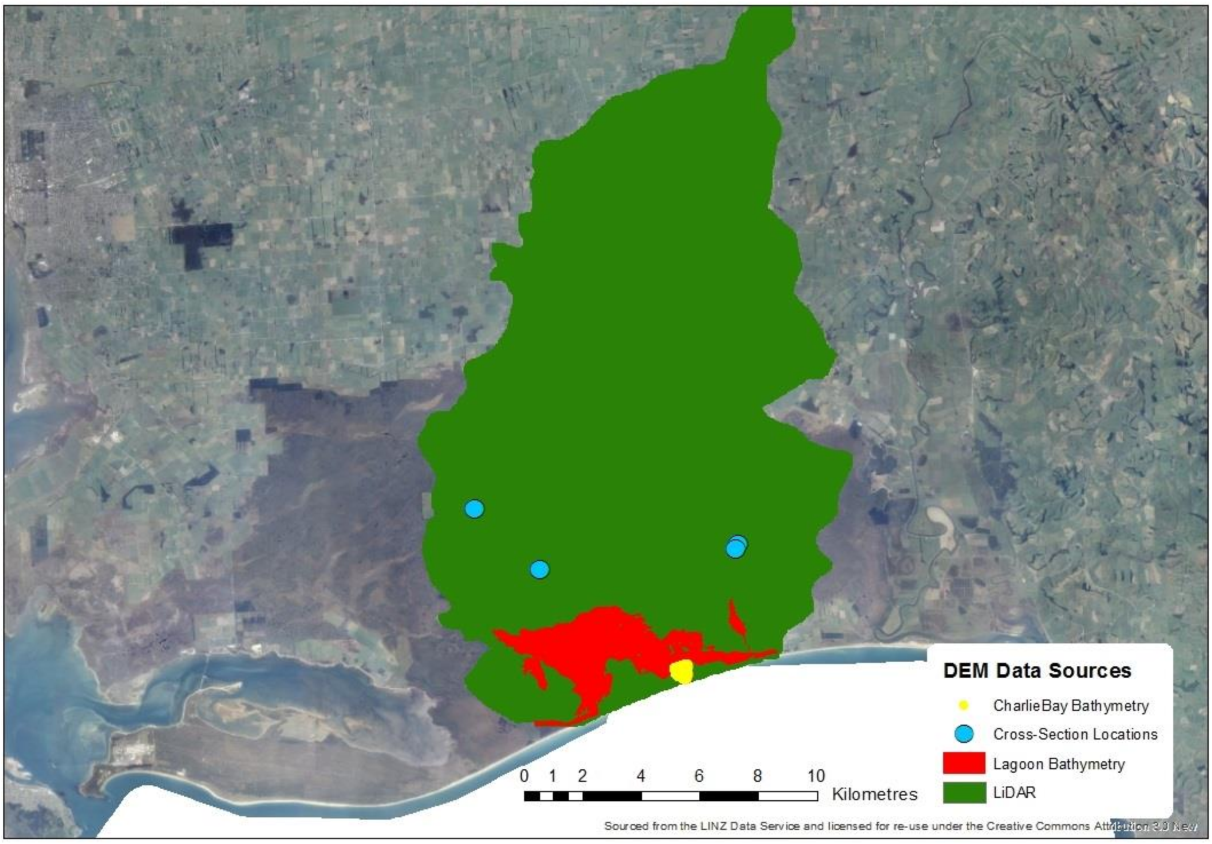

Figure 3-1: Data sources used to generate the final DEM for the simple 'bathtub' modelling.

3.2 Results

Figure 3-2 maps inundation extents derived from the simple bathtub model for Waituna Lagoon water levels from 0.5 m to 2.5 m at 0.5 m intervals. Figure 3-3 maps inundation extents for three additional lagoon water levels of specific relevance to the current or possible future management regime (1.5, 1.8 and 2.3 m).

The maps show that the area of land inundated by lagoon levels up to 2.5 m is generally confined to wetlands around the lagoon margins. The areas where the static lagoon level inundates farmland are relatively minor and generally around the mouths of the three main tributary creeks: Waituna, Moffatt and Carran. The impact of lagoon levels on land around Waituna and Carran Creeks is explored further in Stage 2.

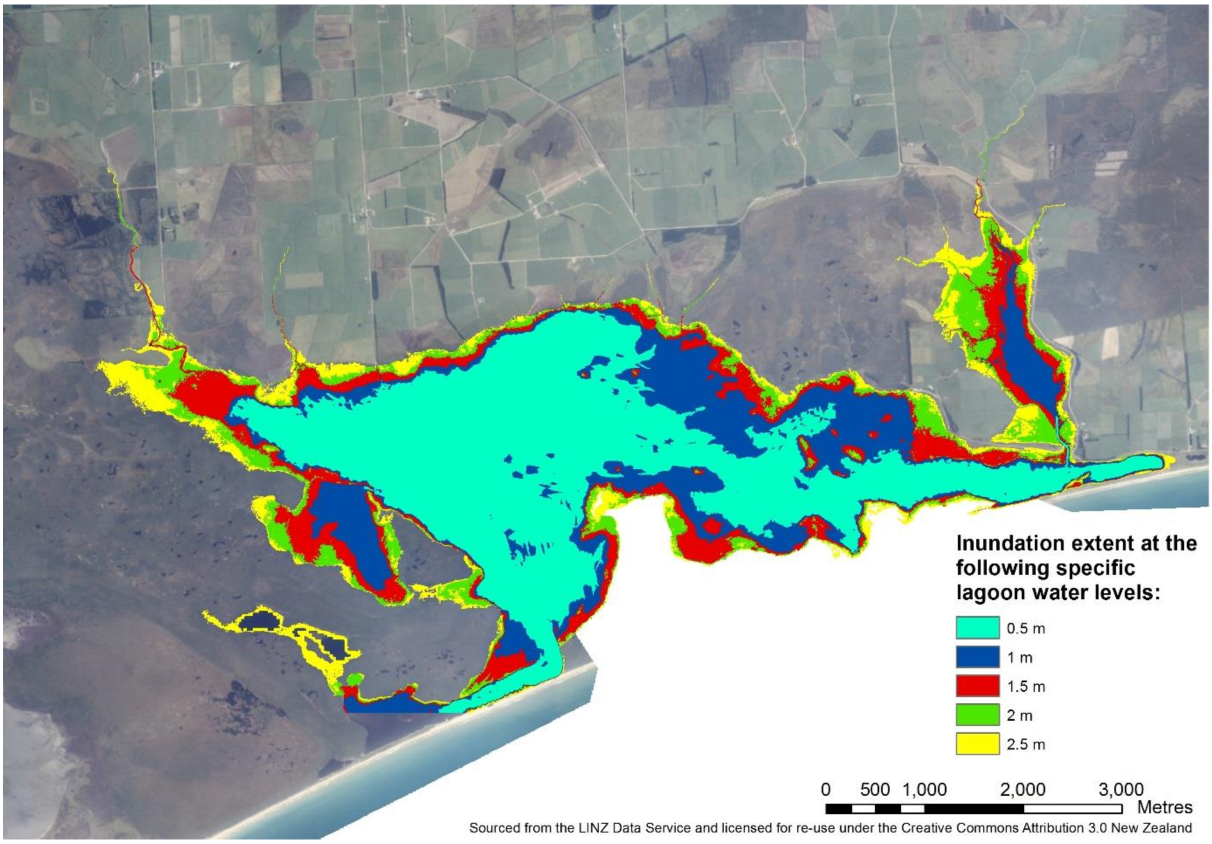

Figure 3-2: Inundation extent for Waituna Lagoon levels at 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. Inundation extents are derived from the simple 'bathtub' model.

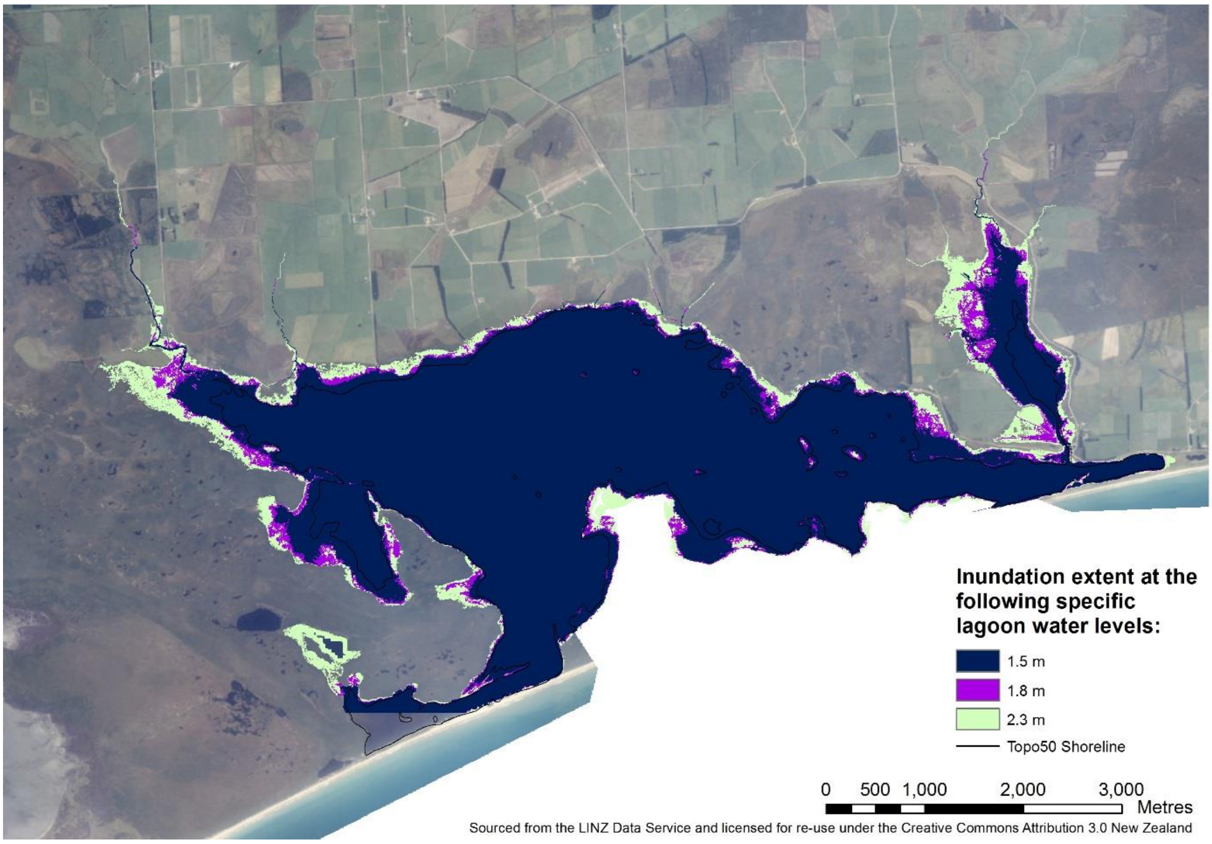

Figure 3-3: Inundation extent for Waituna Lagoon levels at 1.5 m, 1.8 m, and 2.3 m Inundation extents are derived from the simple 'bathtub' model.

4 Stage 2: Hydraulic modelling

4.1 Building the models

Modelling was carried out using DHI's MIKE HYDRO RIVER (Release 2016) modelling package which is a successor of the MIKE-11 modelling tool that is widely used both in New Zealand and internationally.

Three one-dimensional hydraulic models were constructed, one representing a 6.52 km reach of Waituna Creek from the Marshall Road hydrology recorder down to the Waituna Lagoon, another a 5.02 km reach of Carran Creek from 1.5 km upstream of Waituna Lagoon Road down to Waituna Lagoon, and a third representing a 3.95 km reach of Moffat Creek from upstream of Moffat Road down to Waituna Lagoon. Figure 4-1 shows the modelled Waituna Creek reach (bottom left plot) and modelled Carran Creek reach (bottom right plot). Locations of surveyed cross-sections used in the models and downstream chainage are also shown.

Cross-sections were derived from the following sources:

- The December 2015 survey conducted by TrueSouth Survey Services Ltd for Waituna and Carran Creeks. The surveyed cross-sections were extended where necessary using the LiDAR based DEM derived in Stage 1, to give a wider topographic representation of the stream channel and surrounds.
- The March 2017 survey conducted by TrueSouth Survey Services Ltd for Moffat Creek.
- Directly from the LiDAR DEM derived in Stage 1 (within Waituna Lagoon and Little Lake Waituna).

In Waituna Creek, TrueSouth were unable to survey closer to the lagoon than cross-section W-1 as the combination of dense plant growth and wide channel made surveying by boat or on foot very challenging. To provide definition of the channel close to its exit into the lagoon, an artificial cross-section (W1-A) was added at chainage 6.176 km. This cross-section replicates cross-section W-1 but with an adjustment to level of -1.5 m, to match the local thalweg slope between cross-sections W-1 and its nearest cross-section upstream (i.e., W-2). The model could be improved by an additional bathymetric survey between cross-section W1 and the lagoon.

Table 4-1, Table 4-2 and Table 4-3 document the location of key modelled cross-sections for the Waituna Creek, Carran Creek and Moffat Creek models, respectively. Chainage refers to the distance along the river channel from the start of the modelled reach to any given location.

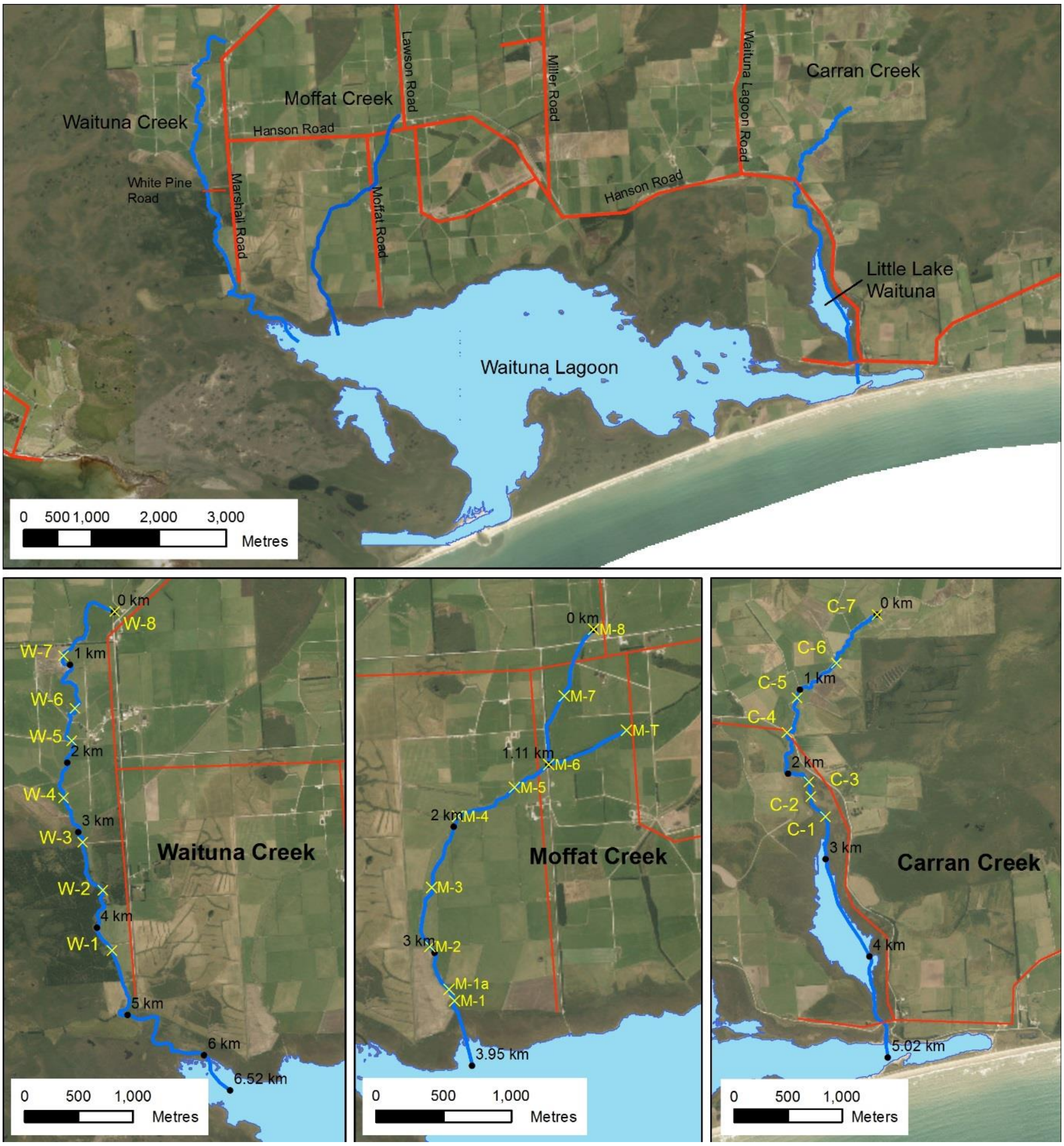

Figure 4-1: Maps of Waituna Lagoon and the modelled creeks. Blue line shows the modelled reach. Yellow crosses show the location of cross-sections surveyed by TrueSouth in December 2015. Black dots show distance from the start of the modelled reach (chainage). *Aerial imagery sourced from the LINZ Data Service https://data.linz.govt.nz/layer/1934-southland-075m-rural-aerial-photos-2005-2011/ and licensed by The Southland Consortium (Southland District Council, Gore District Council, Environment Southland, and Department of Conservation) for re-use under the Creative Commons Attribution 3.0 New Zealand licence*.

Table 4-1: Waituna Creek - location of key modelled cross-sections.

Cross-section	Chainage (km)	Location description
W-8	0.000	Marshall Road Hydrology Recorder Site
W-7	0.862	0.86 km downstream of recorder site
W-6	1.594	Marshall Road Farm Trustees Ltd
W-5	1.992	Marshall Road Farm Trustees Ltd Bridge
W-4	2.608	0.5 km upstream of White Pine Road
W-3	3.116	At White Pine Road
W-2	3.640	0.5 km downstream of White Pine Road
W-1	4.303	1 km downstream of White Pine Road
W-1A	6.176	Outlet to Waituna Lagoon
W-LG	6.520	Lagoon

Table 4-2: Carran Creek - location of key modelled cross-sections.

Cross-section	Chainage (km)	Location description
C-7	0.000	1.5 km upstream of Waituna Lagoon Road Bridge
C-6	0.549	1 km upstream of Waituna Lagoon Road Bridge
C-5	1.111	0.4 km upstream of Waituna Lagoon Road Bridge
C-4	1.527	At Waituna Lagoon Road Bridge
C-3	2.238	0.65 km downstream of Waituna Lagoon Road Bridge
C-2	2.377	0.8 km downstream of Waituna Lagoon Road Bridge
C-1	2.617	Near outflow at Little Lake Waituna
E-12	2.822	Little Lake Waituna
E-2	4.710	Little Lake Waituna
E-1B	4.856	Channel immediately upstream of outlet to Waituna Lagoon
E-1	5.020	Lagoon

Table 4-3: Moffat Creek - location of key modelled cross-sections.

Cross-section	Chainage (km)	Location description
M-8	0.000	130 m upstream of Hanson Road
M-Tributary	0	Upper tributary
M-7	0.557	0.5 km m upstream of Moffat Road
M-6	1.110	At Moffat Road Bridge
M-5	1.420	0.3 km Downstream of Moffat Road
M-4	1.914	0.8 km Downstream of Moffat Road
M-3	2.487	1.15 km downstream of Moffat Road
M-2	2.973	2 km downstream of Moffat Road
M-1a	3.343	2.4 km downstream of Moffat Road
M-1	3.437	Near outflow at Waituna Lagoon
M-OT	3.524	Channel immediately upstream of outlet to Waituna Lagoon
M-LG	3.949	Lagoon

4.2 Calibrating the models

In hydraulic modelling *roughness* represents a channels frictional resistance to flow. For the Waituna, Carran and Moffat Creek models roughness was specified at each cross-section using Manning's n coefficient, where lower values of the coefficient indicate less flow resistance (i.e. shallower faster flow will occur) and higher values of the coefficient indicate greater flow resistance (i.e. deeper slower flow). Roughness is influenced by many factors including bed material and vegetation/plant growth. Typical values of Manning's n are available from the literature but calibration is necessary in order to adjust roughness values so that the model correctly predicts observed water level for a known flow. The range of Manning's n potentially applicable to the Waituna, Carran and Moffat Creek models is given in Table 4-4 (Chow, 1959).

Table 4-4: Range of Manning's n values potentially applicable to Waituna and Carran Creek models. Based on Chow 1959 Table 5-6.

Channel description	Manning's n		
	Minimum	Normal	Maximum
Earth, straight and uniform: Clean recently dredged/excavated	0.016	0.018	0.020
Earth, straight and uniform: With short grass, few weeds[1]	0.022	0.027	0.033
Earth, winding and sluggish: Stony bottom and weedy[1] banks	0.025	0.035	0.040
Channels not maintained, weeds[1] and brush uncut: Clean bottom, brush on sides	0.040	0.050	0.080
Channels not maintained, weeds[1] and brush uncut: Dense weeds high as flow depth	0.050	0.080	0.120
Channels not maintained, weeds[1] and brush uncut: Dense brush, high flow depth	0.080	0.100	0.140
Very weedy[1] reaches, deep pools, or floodways with heavy stands of timber and underbrush	0.075	0.100	0.150

1. The term 'weeds' as used in hydraulics literature refers to any plants increasing flow resistance and does not imply invasive/alien species.

The Waituna and Carran Creek models were calibrated against water level profiles derived from water levels recorded at each cross-section by TrueSouth during the surveys. During the surveys a flow gauging was undertaken at each of the surveyed cross-sections. The flow gauging was done using an ADCP StreamPro, except at the Marshall Road Flow Recorder site (section W-8) where a Pygmy current meter was used. At each cross-section plant growth was cleared 3 m upstream and downstream of the gauging site to enable a reliable measurement of water depth and flow throughout the gauged cross-section.

These gaugings were used to assess flow inputs to the upstream boundary of the modelled reach and lateral inflows to the channel downstream throughout the reach arising from groundwater, field-drains and small tributaries. For the Waituna and Carran Creek models, the recorded water level at the Waituna Lagoon Monitoring Platform hydrometric site was used as the downstream boundary condition. The monitoring platform had ceased operation when the Moffat Creek survey was completed and the Waghorns Road lagoon water level recorder was used for the Moffat Creek downstream boundary. No allowance was made for wind setup in the lagoon. Gauging notes recorded during the survey (key metadata parameters of which are summarised in Appendix A) indicated that the wind was light to moderate at the time that gaugings were taken at sections likely to be affected by lagoon level. Given this, wind setup would not have been significant.

We note, the purpose of the modelling was to assess backwater effects at low to moderate flows, not under flood conditions. Therefore calibration at the relatively low flow conditions during the December 2015 survey is acceptable for Waituna and Carran Creek models. The calibration, however, would need to be revisited if the models were to be applied to simulate flood flows.

4.2.1 Calibrating the Waituna Creek model

Table 4-5 summarises the main channel inflow and downstream water level boundary conditions assumed for the Waituna Creek model calibration. For Waituna Creek, flow gaugings at cross-sections showed little variation through the modelled reach. On this basis, no lateral inflows are included in the model. Based on recorded water levels in the lagoon, we specified a linearly varying lagoon level water level that ramped down from 1.26 m to 1.14 m over the 7 hour gauging period on 10 December 2015.

Table 4-5: Waituna Creek model - boundary conditions for the calibration trials.

Boundary conditions/Flow inputs	River distance (km)	Flow (m^3/s)	Water Level (m)
Upstream flow boundary condition	0.00	0.477	
Downstream water level boundary condition	6.52		1.26 – 1.14 m

Figure 4-2 compares the surveyed water level profile from the 10 December 2015 survey data, with that derived from the calibrated model. In order to give a fair comparison, given that the downstream water level is variable, both measured and simulated profiles compare water levels at the recorded start time of the gauging at each gauging site. In practice, the differences in water levels over time resulting from the changing lagoon level are very slight and only affect cross-sections downstream of section W-3.

A good match is shown between the modelled and observed water levels at all cross-sections except at cross-section W-5 where the model under-predicts the water level by 0.17 m. Given that this effect is local, the calibration is considered acceptable.

Figure 4-2 also shows the calibrated Manning's n roughness values. Values are specified at the surveyed sections. Manning's n roughness values at computational nodes between cross-sections are then determined by linear interpolation. The Manning's n roughness at the channel outlet into the lagoon (i.e. at cross-section W-1A), and in the lagoon itself, have been taken as 0.05. This means that roughness ramps up from 0.05 to 0.12 between cross-sections W-1A and W-1.

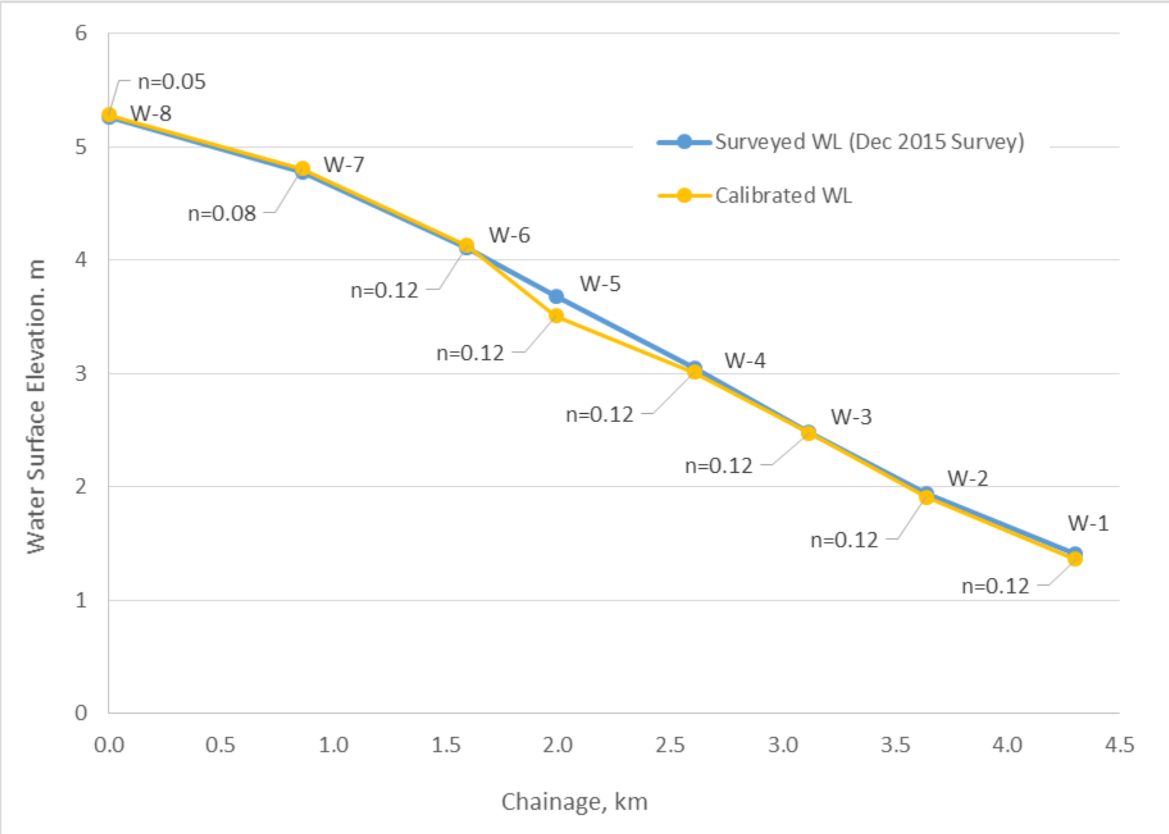

Figure 4-2: Comparison of surveyed and calibrated water surface profiles for Waituna Creek. Calibrated Manning's n roughness values are also shown.

Gauging notes (summarised in Appendix A) describe the main channel as affected by plant growth at cross-sections W-6 through to W-3. Plants in the channel cause a significant increase in roughness (e.g. see Table 4-4) and are the likely cause of the very high roughness coefficient (n=0.12) required to calibrate the model in the middle reach. Other factors which could affect the water level include local constrictions within the channel not captured by the survey (for example a partially blocked culvert or section of elevated bed acting as a weir). Unlike plant growth, which can be widespread, constrictions would only cause a relatively local effect. It is likely that the difference in water level at cross-section W-5 could be caused by a local constriction between this cross section and cross-section W-4.

In fact, dense plant growth proved to be a significant problem during the survey. An echo-sounder survey of longitudinal bed profiles had been planned as part of the survey. TrueSouth attempted this, but had to abandon it as "the infestation of thick [plants] encountered during the survey prevented the capture of reliable bed soundings" (Thompson 2015). The cover of plants ranged from minimal (at site W-1) to prolific (see Appendix A).

4.2.2 Calibrating the Carran Creek model

An initial calibration was performed using the gauging data and water level measurements collected on 9 December 2015.

Table 4-6 lists the boundary conditions and lateral flow inputs applied in the calibration, to match gauged flows during the 9 December 2015 survey. The lagoon level on the day, which was constant at around 1.285 m, is also listed.

Table 4-6: Carran Creek model - boundary conditions and lateral inflows for the initial calibration event

Boundary conditions/Flow inputs	Chainage, km	Flow, m^3/s	Water Level, m
Upstream flow boundary condition	0.00	0.09	
Downstream water level boundary condition	5.02		1.285
Lateral inflow-(C-6 – C-7)	0.00 – 0.55	0.026	
Lateral inflow-(C-5 – C-6)	0.55-1.11	0.022	
Lateral inflow-(C-4 – C-5)	1.11 – 1.53	0.009	
Lateral inflow-(C-3 – C-4)	1.53 – 2.24	0.009	
Lateral inflow-(C-2 – C-3)	2.24 – 2.38	0.031	

Figure 4-3 compares the water surface profile for the initial calibration event, in which Manning's n is set to 0.15 globally, with the surveyed water surface profile. This initial calibration works well downstream from cross-section C-4 but it significantly under-predicts water surface elevation upstream of this location.

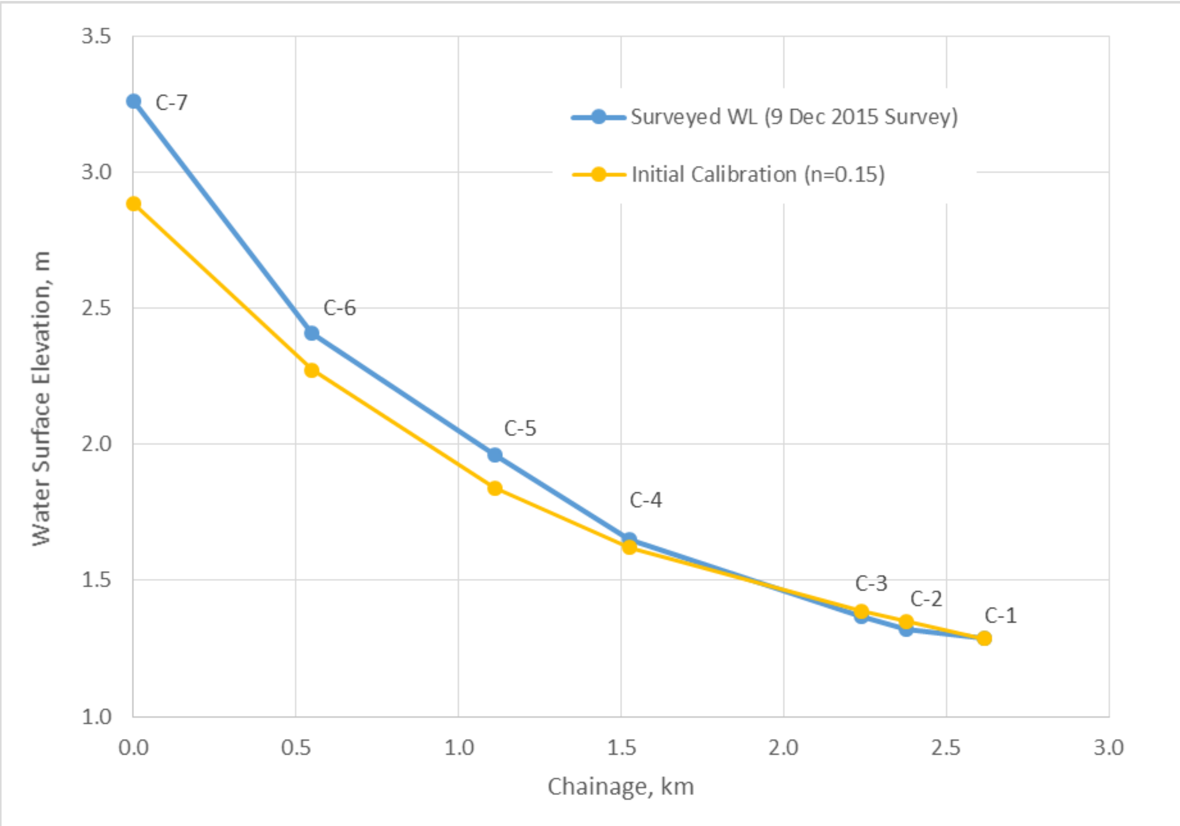

Figure 4-3: Comparison of surveyed water surface profiles with that for an initial calibration of the Carran Creek model. Manning's n roughness is set to 0.15 globally.

The poor calibration upstream of cross-section C-4 is likely due to partial blockage of the low flow channel by dense plants. This is supported by photographs taken during the survey at sites C-6 and C-7 (Figure 4-4) showing that the low flow channel is significantly narrowed by mats of reeds growing on the banks. This blockage effect would be reduced at higher flows (as the plants are flattened by the higher flow velocities) and therefore the high roughness needed to calibrate to it would be unrealistic at higher flows. Local flow constrictions not captured by the cross-section survey could also be raising the water level in the creek. This is a potential cause of difference between the modelled and observed water levels but by their nature any effects would be localised so it is unlikely that this is the cause of differences over ~1.5 km of channel.

Figure 4-4: Photographs at gauging sites C-6 (top) and C-7 (bottom) showing plant growth. The photographs were taken during the flow gauging survey on 9 Dec 2015.

Additional water level data on Carran Creek was available from a longitudinal water surface profile survey undertaken by Environment Southland on 11 July 2012. The flow in Waituna Creek at the time of the survey, based on rated flow from the Waituna at Marshall Road recorder, was steady at around 0.79 m^3/s. Applying this to Environment Southland's equation relating flow in Carran Creek to recorded flow in Waituna Creek, the flow in Carran Creek at the time of the survey is estimated to be 0.204 m^3/s. This equation gives flow at the Carran Creek telemetry site which is close to the upstream extent of the model (i.e., to cross-section C-7). This equation was calculated from a period of concurrent flow observations and has been demonstrated to be reliable for hindcasting flow in Carran Creek (r^2 = 0.97, pers. comm. Chris Jenkins).

We undertook a second calibration of the Carran Creek model using the 11 July 2012 water surface elevation data as a calibration profile. Table 4-7 lists the inflow and water level boundary conditions that were applied. Inflows were not gauged during 11 July 2012, so no data was available from which to directly assess lateral inflows. Instead, lateral inflows are assumed to have the same proportion to the main channel inflow as in the December 2015 survey, totalling 52% of the main channel flow.

As a check on the lateral inflows, we calculated the catchment area for the whole Carran Creek catchment to be 49.25 km^2 and the catchment downstream of cross-section C-7 to be 23.12 km^2. The proportion of the catchment below cross-section C-7 is therefore 47%, which is close to our estimate for lateral inflows totalling 52% of the main channel flow. This confirms that our estimate for lateral inflows, totalling 52% of the main channel flow, is reasonable.

Table 4-7: Carran Creek model - boundary conditions and lateral inflows for the second calibration event

Boundary conditions/Flow inputs	Chainage, km	Flow, m^3/s	Water Level, m
Upstream flow boundary condition	0.00	0.204	
Downstream water level boundary condition	5.02		0.45
Lateral inflow-(C-6 – C-7)	0.00 – 0.55	0.059	
Lateral inflow-(C-5 – C-6)	0.55-1.11	0.05	
Lateral inflow-(C-4 – C-5)	1.11 – 1.53	0.02	
Lateral inflow-(C-3 – C-4)	1.53 – 2.24	0.02	
Lateral inflow-(C-2 – C-3)	2.24 – 2.38	0.07	

Figure 4-5 compares modelled and surveyed water surface profile for the second calibration event after calibration. Manning's n has been set to 0.08 globally. Good agreement is shown over the reach for which survey data is available (i.e., from chainage 0.3 to 1.44 km).

The final roughness calibration (Table 4-8) is a combination of results from the two calibration events.

Table 4-8: Carran Creek model - final roughness calibration.

Sub Reach (Chainage to-from, km)	Manning's n	Basis
0.00 - 1.527	0.08	9 Dec 2015 Water Level Survey
1.54 - 5.02	0.15	11 Jul 2013 Water Level. Survey

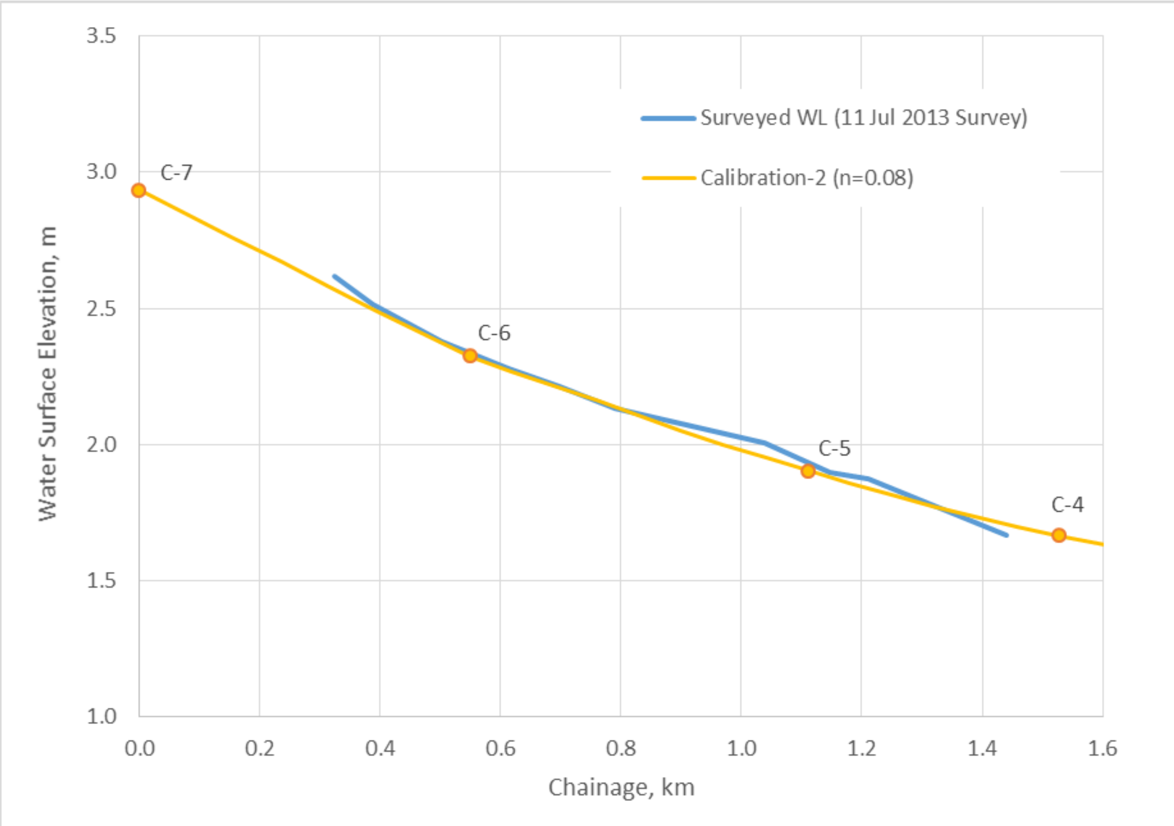

Figure 4-5: Comparison of surveyed water surface profiles with that for the second calibration of the Carran Creek model. Manning's n roughness is set to 0.08 globally.

4.2.3 Calibrating the Moffat Creek model

Table 4-9 lists the main channel inflow and downstream water boundary conditions applied in the calibration to match water surface profile during 1 and 3 March 2017 survey. The water level in the lagoon on the day of survey was constant at around 1.37 m.

Table 4-9: Moffat Creek model – boundary conditions for the calibration model.

Boundary conditions/Flow inputs	River distance (km)	Flow (m^3/s)	Water Level (m)
Upstream flow boundary condition-Moffat Creek	0	0.017	
Downstream water level boundary condition	3.73		1.37
Lateral inflow-(M-7 – M-8)	0 – 0.56	0.0035	
Upstream flow boundary condition-Moffat Tributary	0	0.0035	
Lateral inflow-(M-5 – M-6)	1.11 – 1.42	0.023	
Lateral inflow-(M-4 – M-5)	1.42 – 1.91	0.007	
Lateral inflow-(M-3 – M-4)	1.91 – 2.49	0.006	
Lateral inflow-(M-2 – M-3)	2.49 – 2.97	0.026	
Lateral inflow-(M-1a – M-2)	2.97 – 3.34	0.035	

Figure 4-6 compares calibrated model and surveyed water surface profile for the calibration event. Figure 4-6 also shows the calibrated Manning's n roughness values. Values are specified at the surveyed sections. Linear interpolation was used to determine roughness values at computational nodes between cross-sections. The Manning's n roughness at three downstream cross sections (i.e. at cross section M-2, M-1 and M-1a) have been taken as 0.2. Also, for upstream cross sections (from cross sections M-3 to M-8), Manning's n roughness of 0.35 makes good agreement between the modelled and observed water levels over the reach.

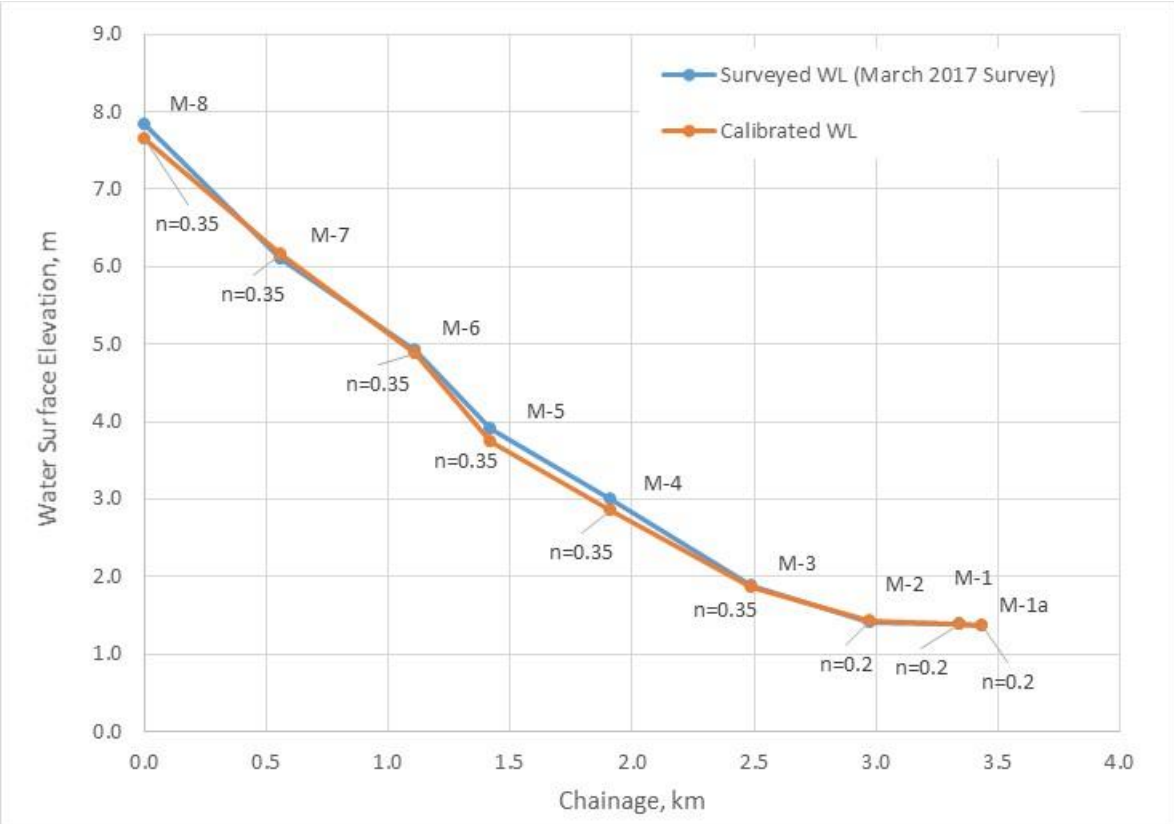

Figure 4-6: Comparison of surveyed and calibrated water surface profiles for Moffat Creek. Calibrated Manning's n roughness values are also shown.

4.3 Applying the models

Following calibration, the now calibrated hydraulic models of Waituna Creek, Carran Creek and Moffat Creek were used to assess backwater effects for four scenarios comprising two steady flows: 1) mean flow (Q_{mean}); and 2) a higher but not extreme flow, taken as the 90 percentile high flow (Q_{90}), in conjunction with two roughness categories: 1) "channel vegetated"; and 2) "channel cleared". For each scenario, steady-state backwater profiles were extracted for a range of lagoon levels.

Based on analysis of rated flow data from the Waituna Creek at Marshall Road recorder for the period from 13 August 2001 to 31 Dec 2015 (the full period of record for this site), the mean flow and 90 percentile high flow at site W-8 in Waituna Creek, were calculated to be 1.66 m^3/s and 4.15 m^3/s, respectively.

Then, applying Environment Southland's equation relating flow in Carran Creek and Moffat Creek to flow in Waituna Creek, the mean flows at site C-7 in Carran Creek and M-8 in Moffat Creek, for the same period, are estimated to be 0.300 m^3/s and 0.234 m^3/s respectively, and the 90 percentile high flows, to be 0.76 m^3/s and 0.514 m^3/s respectively.

As for the calibration runs, lateral inflows into the main channel of Waituna Creek are assumed to be negligible based on the negligible increase in flow observed during the 10 December 2015 flow gaugings. This is consistent with its large upstream catchment and relatively small catchment within the modelled reach. For Carran Creek and Moffat Creek lateral inflows are significant and were specified using the same proportions to inflow as determined from the 9 December 2015, and 8 March 2017 flow gaugings, respectively.

Lagoon levels ranging from 0.5 m to 2.5 m at 0.5 m increments were simulated. As well, three additional lagoon levels: 1.2 m, 1.8 m and 2.3 m that were of special interest, were also simulated.

Environment Southland periodically clear Waituna Creek, Moffat Creek and Carran Creek of plants, using a backhoe to scrape the sides and bottom of the channel where accessible. The model calibration highlighted the significant effect of plants on creek water levels. It is likely that the variable effect of plant growth represents the biggest source of uncertainty in this modelling study so two roughness scenarios were modelled to represent this. The two roughness categories: 1) “channel vegetated”; and 2) “channel cleared”, correspond to conditions before and after channel clearing. Roughness for the two categories is defined as follows:

- For the “channel vegetated” category, the final roughness calibrations as described in Section 4.2.1 for Waituna Creek, Section 4.2.2 for Carran Creek and Section 4.2.3 for Moffat Creek, have been applied. Use of the roughness calibrations is consistent with high vegetation on the banks and sides in some reaches of Waituna and Carran creeks, as was the case at the time of the December 2015 survey (as described in flow gauging notes and shown in photographs).
- For the “channel cleared” category, a constant Manning’s n roughness value of 0.05 is considered suitable and has been applied.

By comparing the results of the “channel vegetated” and “channel cleared” simulations it is possible to isolate the effects of plant growth and understand the level of uncertainty in the model results due to this source of variability.

The modelling does not consider wind set-up in Waituna Lagoon, although this may be done at a later stage. Any set-up should be added to the lagoon level, before the relationships derived here are used to estimate the effect on the creek upstream.

4.4 Results

The model results are presented using long section profiles of creek water level as well as maps showing the area of land impacted. We have mapped two different severities of impact:

1. Land which is inundated. These areas have been mapped as land where the ground level in the LiDAR derived digital elevation model is lower than the modelled water level in the creek.
2. Land which is potentially influenced by poor drainage. The maps identify farm land adjacent to the main river channel that is within a threshold distance of the water level in the main channel. The basis for this is that flow in the field drains, will start to be influenced by backwater effects when their downstream end becomes drowned. Two different depth thresholds, 1 m and 2 m, were applied in order to represent the range of depths at which field drains are likely to occur. The plots, therefore give an

indication of areas that could have reduced drainage due to lagoon level effects. It is recognised that this is a simplistic assumption for the calculation of drainage affected areas but we feel it provides a useful first-cut mapping of areas where land drainage is potentially impeded.

When interpreting the long section plots and the maps it is possible to identify the effects of lagoon level by comparing the results for a given lagoon level with the results for the low (0.5 m) lagoon level simulation. The increase in water level (long-sections) or affected area (maps) from this low lagoon level baseline represents the effect of the lagoon. This is illustrated in Figure 4-7. Reaches where the water level or affected area does not change between different lagoon levels indicate that inundation or poor drainage results from the combination of creek flow and roughness irrespective of lagoon level.

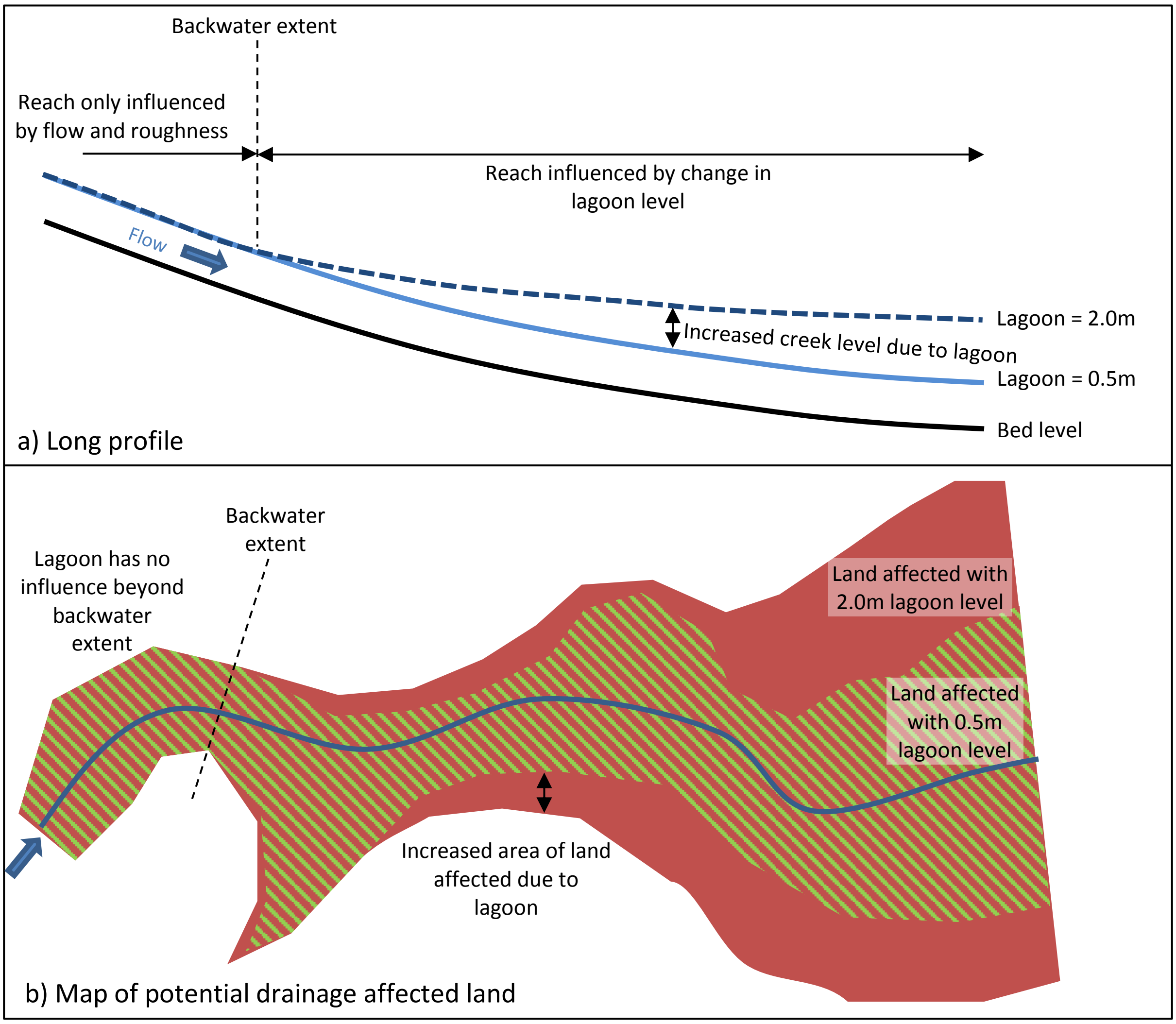

Figure 4-7: Illustration of how increase in water level above the low lagoon level scenario represents the effect of the lagoon. a) Shows long section. b) Shows map view.

The backwater extent has been tabulated and marked on the inundation maps. The backwater extent has been defined as the upstream limit of the reach where the lagoon affected creek water level is higher than the creek level under low lagoon level conditions. A consistent depth threshold of

0.02 m has been applied when calculating backwater extent i.e. upstream of the backwater extent the lagoon level has a negligible (< 0.02 m) effect on water levels.

4.4.1 Waituna Creek backwater profiles and extent

Figure 4-8 plots backwater profiles for Waituna Creek. Four plots are shown covering backwater profiles for the two flow cases (Q_{mean} and Q_{90}) and for two roughness categories ("channel cleared" and "channel vegetated"). Each plot shows water surface profiles for a range of lagoon levels from 0.5 m to 2.5 m and a bed thalweg profile. The bed thalweg level is shown as a solid line where it has been interpolated between surveyed cross-sections and as a dotted line, where it has been extrapolated.

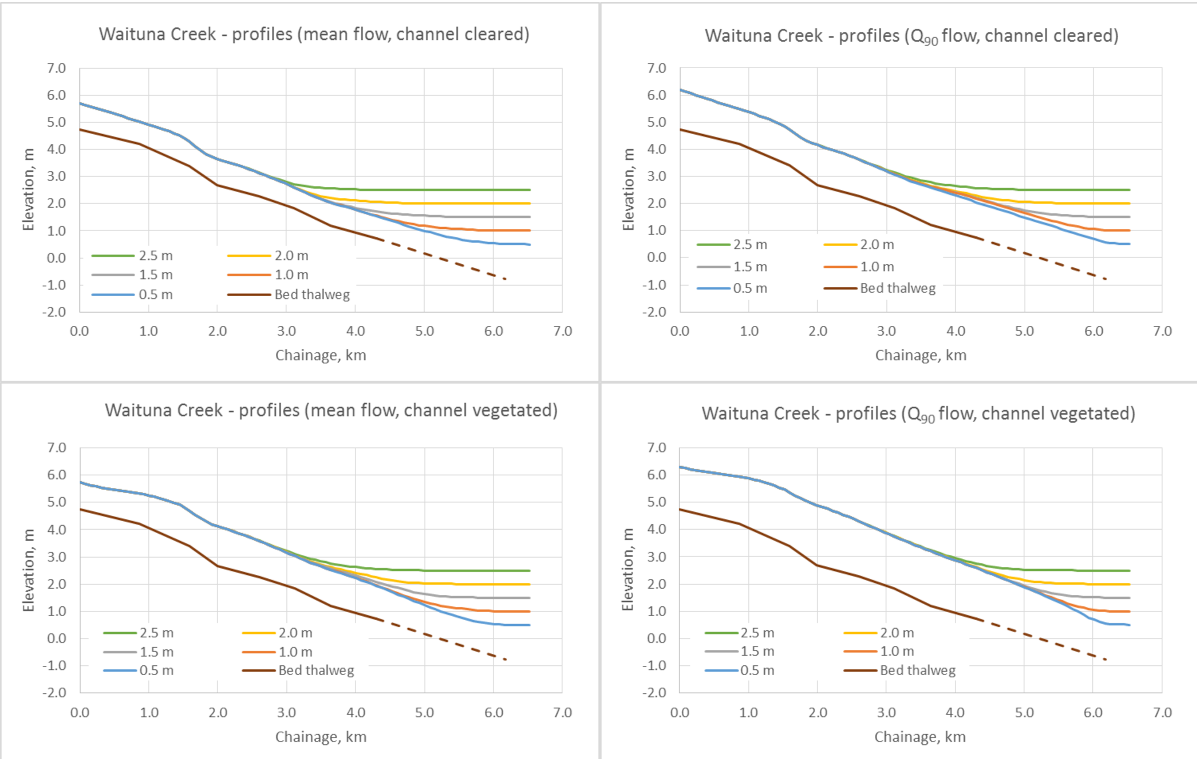

Figure 4-8: Waituna Creek backwater profiles. Left hand side plots are for mean flow and right hand side plots are for the 90 percentile high flow. Within each vertical slice, the top plot is with "channel cleared" and the bottom plot is with "channel vegetated".

As well as the backwater profiles, maps of inundation extent for lagoon water levels of 1.0 m, 1.5 m, 2.0 m and 2.5 m were created and are shown in Appendix B. Four maps are shown, one for each flow and roughness characterisation scenario. Each plot shows, as well as inundated land area, red lines indicating the backwater extent in the main channel for a range of lagoon water levels. Table 4-10 provides the same information in tabular form, with backwater extent given in terms of chainage along the channel.

Table 4-10: Waituna Creek – the chainage in kilometres of the backwater extent for the four scenarios at different Waituna Lagoon water levels. Note: Since chainage increases in a downstream direction, higher chainages represent a lesser backwater extent.

	Channel Cleared		Channel Vegetated	
Lagoon WL, m	Q_{mean}	Q_{90}	Q_{mean}	Q_{90}
1.0	4.31	3.30	4.34	5.25
1.2	4.02	3.30	3.91	5.06
1.5	3.60	3.27	3.31	4.71
1.8	3.32	3.19	3.13	4.42
2.0	3.16	3.10	3.04	4.17
2.3	2.92	2.87	2.84	3.59
2.5	2.73	2.72	2.68	3.36

Key results relating to backwater extent in Waituna Creek are:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was to around chainage 2.7 km and occurred at a lagoon level of 2.5 m. At this lagoon level, three of the four scenarios have very similar backwater extents. The exception is the "Q_{90} - Channel Vegetated" scenario which, because of raised water levels drowning out some of the backwater effect, gives a reduced backwater extent.
- For each lagoon water level, the "Q_{90} -Channel Vegetated" scenario gives the least backwater extents. This is because the water level due to flow is already high in this scenario so the lagoon has little further effect. The other three scenarios give backwater extents that are higher and that are broadly similar except at low lagoon levels (WL ≤ 1.5 m), where the "Q_{90} -Channel Cleared" scenario gives backwater extents that are up to 1 km further than the other two due to the effect of the higher flow raising water levels in the channel near the lagoon, but not so much as to drown out the backwater effect.
- Farmland inundated by high lagoon static water level or backwater from the lagoon, is mainly within an area on the true left of the channel south of a farm access road with connection to Marshall Road about 1 km south of White Pine Road (downstream of chainage 4.3 km). At the 90 percentile high flow, significant inundation of this area occurs even at low lagoon level when the channel is vegetated, indicating that inundation is related to restriction of the channel rather than the lagoon level. With the channel cleared, or at mean flow, the effect of lagoon level does become important. Under these scenarios, significant inundation then occurs only when the lagoon level equals or exceeds 2.0 m.

4.4.2 Carran Creek backwater profiles and extent

Figure 4-9 plots backwater profiles for Carran Creek. Four plots are shown as described in Section 4.4.1 for Waituna Creek. Each plot shows profiles of water surface elevation for a range of lagoon levels from 0.5 m to 2.5 m and a bed thalweg profile.

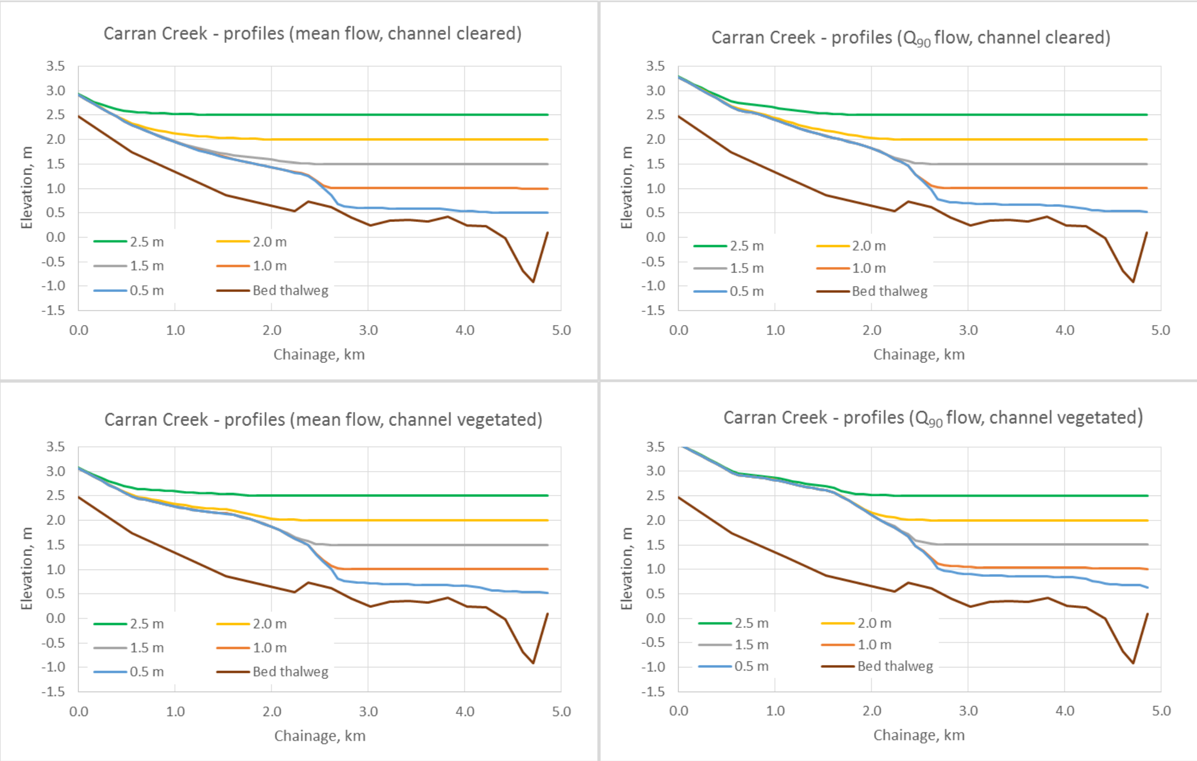

Figure 4-9: Carran Creek backwater profiles. Left hand side plots are for mean flow and right hand side plots are for the 90 percentile high flow. Within each vertical slice, the top plot is with "channel cleared" and the bottom plot is with "channel vegetated".

Maps of inundation and backwater extent have been plotted for Carran Creek as for Waituna Creek (see Section 4.4.1), and are shown in Appendix C. Table 4-11 summarises backwater extents for the four scenarios.

Table 4-11: Carran Creek – the chainage in kilometres of the backwater extent for the four scenarios at different Waituna Lagoon water levels. Note: Since chainage increases in a downstream direction higher chainages represent a lower the backwater extent.

	Channel Cleared		Channel Vegetated	
Lagoon WL, m	Q_{mean}	Q_{90}	Q_{mean}	Q_{90}
1.0	2.42	2.49	2.49	2.57
1.2	1.84	2.40	2.40	2.44
1.5	1.05	2.18	2.14	2.25
1.8	0.65	1.11	1.11	2.03
2.0	0.47	0.64	0.55	1.93
2.3	0.23	0.27	0.21	1.18
2.5	0.06	0.07	0.04	0.48

Key results relating to backwater extent in Carran Creek are:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was to about 40 m downstream of cross-section C-7 (i.e. to chainage 0.04 km) and occurred at a lagoon level of 2.5 m. At this lagoon water level, three of the four scenarios have very similar backwater extents. The exception is the "Q_{90} - Channel Vegetated" scenario. As for Waituna Creek, the raised water levels that occur under this scenario drown out some of the backwater effect, thereby giving a reduced backwater extent (to chainage 0.48 km)

- A restriction in the channel at chainage 2.6 km (i.e., at surveyed cross-section C-1) acts as a control (see Figure 4-9). This combined with high roughness when the channel is vegetated raises water levels steeply upstream of this point. As a result, except at lagoon water levels greater than 1.5 m, backwater effects for the two "Channel Vegetated" scenarios, and for the "Q_{mean} - Channel Cleared" scenario, extend upstream only as far as chainage 2.14 km (i.e., to about 0.6 km downstream of Waituna Lagoon Road Bridge).

- For the range of scenarios considered, the extent of inundation (as shown in Appendix D, Figure D-1 to Figure D-8) is determined mostly by lagoon level and is only very slightly affected by plant growth and flow in the main channel. The main area of inundated land is west and north-west of Little Lake Waituna. No significant inundation occurs east of Waituna Lagoon Road or north of Hanson Road.

4.4.3 Moffat Creek backwater profiles and extent

Figure 4-10 plots backwater profiles for Moffat Creek. Four plots are shown as described in section 4.4.1 for Waituna Creek. Each plot shows water surface profiles for a range of lagoon levels from 0.5 m to 2.5 m and bed thalweg profile.

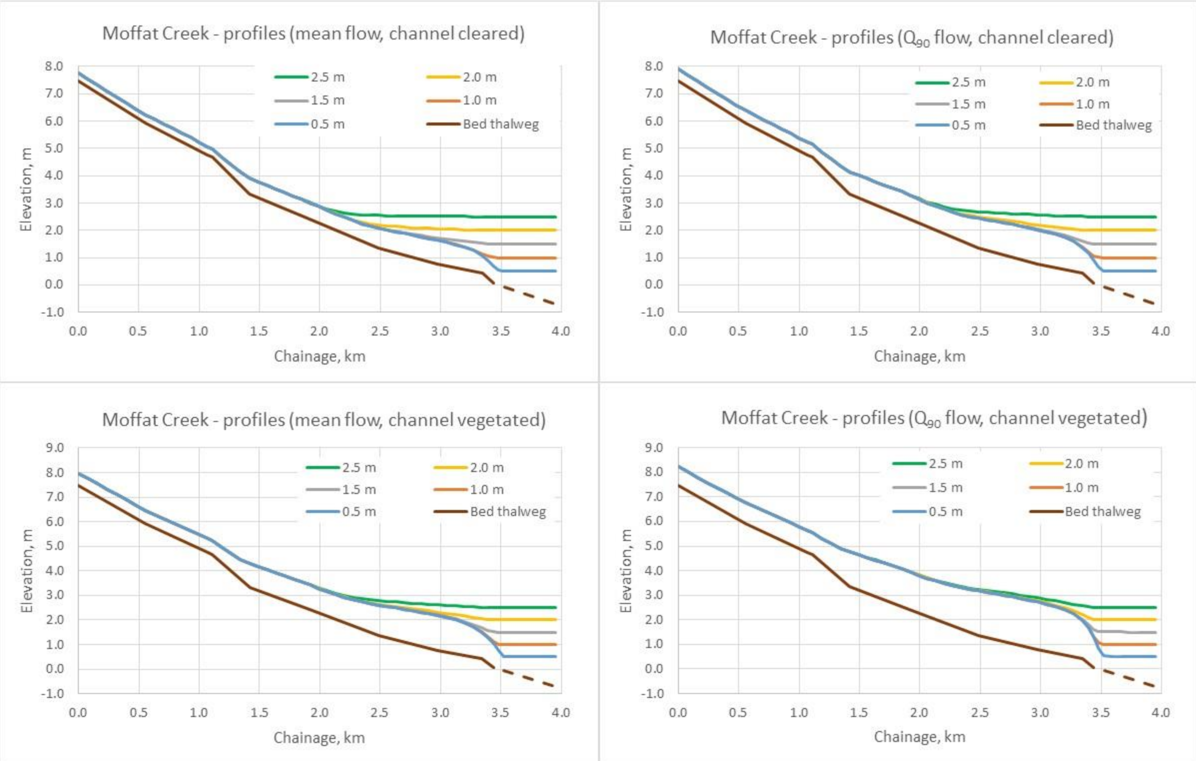

Figure 4-10: Moffat Creek backwater profiles. Left hand side plots are for mean flow and right hand side plots are for the 90 percentile high flow. Within each vertical slice, the top plot is with "channel cleared" and the bottom plot is with "channel vegetated".

Maps of inundation extent for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m were created and are shown in Appendix C. Table 4-12 provides backwater extents for the four scenarios in tabular form.

Table 4-12: Moffat Creek – the chainage in kilometres of the backwater extent for the four scenarios at different Waituna Lagoon water levels. Note: Since chainage increases in a downstream direction, higher chainages represent a lesser backwater extent.

	Channel Cleared		Channel Vegetated	
Lagoon WL, m	Q_{mean}	Q_{90}	Q_{mean}	Q_{90}
1.0	3.25	3.35	3.37	3.42
1.2	3.00	3.23	3.25	3.37
1.5	2.58	2.83	2.93	3.26
1.8	2.34	2.39	2.49	2.97
2.0	2.25	2.25	2.28	2.63
2.3	2.11	2.09	2.09	2.21
2.5	2.01	2.00	1.99	2.07

Key results relating to backwater extent in Moffat Creek are:

- For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was around chainage 2.0 km.
- For each lagoon water level, the 90 percentile high flow with a vegetated main channel scenario gives the least backwater extent. The reason is high water level due to flow in this scenario exceeds the lagoon effect.
- For the range of scenarios considered (as shown in Appendix C, Figure C-1 to Figure C-8), the main area of land inundated by high Waituna lagoon levels is wetland habitat near the Waituna lagoon, not farmland. Little direct inundation of farmland is shown for any of the scenarios.

4.4.4 Waituna Creek – maps of potential drainage affected land

Appendix E and Appendix H provide maps for Waituna Creek of land areas where drainage is potentially affected by backwater or high water effects for two threshold depths: 1.0 and 2.0 m, respectively. Eight maps are shown for each threshold depth, two for each flow-roughness characterisation scenario.

Key results relating to potentially drainage affected land in Waituna Creek are:

- At the 90 percentile high flow, the land area where drainage is potentially affected is much more influenced by high channel roughness than by lagoon water level. As evidence of this, compare the large area of drainage affected land at 1.0 m lagoon level in Figure E-7 with the extent of potentially drainage affected land at all lagoon levels in Figure E-3.
- For the lower flow case (i.e., at mean flow), lagoon water level has a larger effect on the area of potentially drainage affected land (see Figure E-1 and Figure E-5) with the area affected increasing with increase in the lagoon water level. The upstream extent of this area for a 2.5 m lagoon level, under both channel roughness scenarios, is approximately 0.5 km south of White Pine Road.
- Considering a 2m threshold rather than a 1m threshold results in a clear increase in drainage affected land identified under all scenarios, however the increase in area because of increasing lake levels is similar for the 1m and 2m drainage depth analysis.

4.4.5 Carran Creek – maps of potential drainage affected land

Appendix G and Appendix J provide maps of potentially drainage affected land for Carran Creek similar to those described in Section 4.4.4 for Waituna Creek.

Key results relating to potentially drainage affected land in Carran Creek are:

- Downstream of Waituna Lagoon Road Bridge, the dominant influence on the extent of potentially drainage affected land is the Waituna Lagoon water level. Upstream of the bridge, the lagoon level has little effect except at high lagoon levels (WL > 2.0 m), and the dominant influence is channel flow and roughness.

- A swath of land about 500 m wide downstream of Waituna Lagoon Road Bridge and west of Lagoon Road is shown to be potentially drainage affected (1m threshold) even at low lagoon level (taken as 0.5 m).
- At the 90 percentile high flow, Figure G-7 shows a fairly large area of farmland (~ 44 ha) upstream of Waituna Lagoon Road Bridge that is potentially drainage affected (1m threshold) when the channel is weedy. This area reduces in size by about 40%, if the channel is cleared (viz. Figure G-3). For both Q_{90} scenarios, the area with impeded drainage was not dramatically affected by lagoon opening or closing, as there were large areas inundated even when the lagoon was at 0.5m.
- At mean flow, except at high lagoon levels (WL > 2.0 m), very little farmland upstream of Waituna Road Bridge is potentially drainage affected under the 1m threshold, when the channel is clear of plants (viz. Figure G-1). If the channel is instead vegetated then, from Figure G-5, more farmland is potentially drainage affected.
- Considering a 2m threshold rather than a 1m threshold results in a clear increase in drainage affected land identified under all scenarios, however the increase in area because of increasing lake levels is similar for the 1m and 2m drainage depth analysis.

4.4.6 Moffat Creek – maps of potential drainage affected land

Appendix F and Appendix I provide maps for Moffat Creek of land areas where drainage is potentially affected by backwater or high water effects using 1.0 m and 2.0 m threshold depths, respectively. Key results relating to potentially drainage affected land in Moffat Creek are:

- Considering a 1 m threshold depth for the identification of potentially drainage impacted land shows that little land upstream of the lagoon backwater is affected by poor drainage.
- Using a 2 m threshold depth suggests that land further upstream is also potentially affected, but the potentially affected land is confined to an approximately 200 m wide corridor centred on the Creek (or 100 m wide corridor centred on its main tributary).
- At the 90 percentile high flow, comparing the area of drainage affected land between cleared (see Figure F-3) and vegetated (see Figure F-7) channels with 1 m threshold depth indicate that the area where drainage is potentially affected is more influenced by high channel roughness than by lagoon level. However, if a 2 m threshold depth is considered there is no significant difference in potentially drainage affected land under two scenarios of cleared (see Figure I-3) and vegetated (see Figure I-7) main channel.

4.4.7 Sensitivity analysis

A sensitivity analysis was conducted to investigate the sensitivity of the backwater extent calculation to the threshold used for defining the limit of the backwater effect.

To investigate the sensitivity of the backwater extent calculation the calculation was repeated using a 0.05 m threshold and the results compared to the originally calculation using a 0.02 m threshold. For this higher threshold, backwater extents up channel were typically: 200 to 300 m less for Waituna Creek; 70 to 180 m less for Carran Creek; and 20 to 140 m less for Moffat Creek, but the overall pattern of how the extend changed between the different scenarios did not change. The reduction in extent associated with increasing the threshold from 0.02 m to 0.05 m demonstrates how in the most upstream part of the backwater extent (as marked on the maps in Appendix B, Appendix C, Appendix D) the lagoon only a small (2-5 cm) effect on water levels.

The sensitivity of the area of drainage affected land to the depth threshold used for identifying it was investigated by comparing maps of drainage affected land identified using a 1.0 m and 2.0 m thresholds. The 2.0 m threshold was selected to be indicative of locations with very deep field drains. This comparison was done for all three Waituna, Carran and Moffat Creeks for each flow-roughness characterisation. Maps showing the results of these analyses are included in Appendix E to Appendix J and have been discussed under sections 4.4.4 to 4.4.6. In general this sensitivity analysis shows that the deeper threshold does result in a moderate increase in the area of land identified as being impacted but the overall pattern of inundation does not change.

5 Summary and recommendations

5.1 Waituna Creek

1. The furthest backwater extent of Waituna Lagoon up Waituna Creek for the range of lagoon water levels considered (i.e. up to 2.5 m) was to around 400 m upstream of White Pine Road.

2. Of the 4 scenarios modelled, the least backwater extent occurs for the “Q_{90} -Channel Vegetated” scenario. Under this scenario the creek level is very high anyway, so the lagoon level has little impact. The other three scenario gave backwater extents that are higher and broadly similar between scenarios (although varying with lagoon level) except at lower lagoon levels (WL < 1.5 m).

3. Farmland inundated by high lagoon water level or backwater effects from the lagoon is mainly within an area on the true left of the channel south of a farm access road off Marshall Road about 1 km south of White Pine Road. At the 90 percentile high flow, significant inundation of this area occurs even at low lagoon levels when the channel is vegetated, indicating that inundation is related to restriction of the channel rather than the lagoon level. With the channel cleared, or at mean flow, significant inundation occurs only when the lagoon level equals or exceeds 2.0 m.

4. At the 90 percentile high flow, the area of land where drainage is potentially affected is much more influenced by high channel roughness (due to plant growth) than by lagoon water level (including backwater effects). At mean flow, the lagoon water level has a more significant effect, but with more limited up-channel extent.

5.2 Carran Creek

1. For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was to about 400 m downstream of cross-section C-7 (i.e. to chainage 0.4 km) and occurred at a lagoon level of 2.5 m.

2. A restriction in the channel at chainage 2.6 km acts as a control, raising water levels steeply upstream of this point. This limits the extent of backwater effects when lagoon levels are less than 1.5 m, particularly when the channel is vegetated.

3. The main area of land inundated by high Waituna lagoon water levels is west to north-west of Little Lake Waituna. No significant inundation occurs east of Waituna Lagoon Road or north of Hanson Road. The extent of this inundation is due mostly to lagoon level – it is only very slightly affected by channel vegetation and flow.

4. A swath of land about 500 m wide downstream of Waituna Lagoon Road Bridge and west of Lagoon Road is potentially drainage affected even at low lagoon level (taken as 0.5 m), although much of this land is wetland habitat

5. At the 90 percentile high flow, a fairly large area of farmland, upstream of Waituna Lagoon Road Bridge (~44 ha), is potentially drainage affected when the channel is vegetated. This area reduces in size by about 40%, if the channel is cleared.

6. At mean flow very little farmland upstream of Waituna Lagoon Road Bridge is potentially drainage affected, when the channel is clear of plants, although land does start to become

affected once lagoon levels exceed approximately 1.8m. If the channel is instead vegetated then, more farmland is potentially drainage affected but lagoon level has relatively little effect.

5.3 Moffat Creek

1. For the range of Waituna Lagoon water levels considered (i.e., up to 2.5 m), the furthest backwater extent was to about 140 downstream of cross section M-4 (i.e. around 940 m downstream of Moffat Road Bridge).

2. The main area of land inundated by high Waituna lagoon water levels is wetland near the outlet of channel to Waituna Lagoon. A small area of farmland in the lower reaches can inundated due mostly to high lagoon levels rather than channel vegetation and flow.

3. At mean flow, 28 ha of farmland adjacent to the main river channel that is less than 1.0 m above the water level in the main channel is potentially drainage affected when channel is vegetated (under 2.5 m lagoon level). This area reduces to about 25.3 ha if the channel is cleared.

4. At mean flow, area of potentially drainage affected farmland adjacent to the channel with ground elevation less than 2.0 m above the channel water level when channel is vegetated is ~100.3 ha (under 2.5 m lagoon level). This area reduces in size by about 16% if the channel is cleared.

5. At the 90 percentile high flow, a larger area of farmland (~27.4 ha) is potentially drainage affected with 1 m threshold depth when the channel is clear (under 2.5 m lagoon level). This area increases to about 48.1 ha if the channel is vegetated.

6. At the 90 percentile high flow, area of farmland which potentially drainage affected with 2 m threshold depth is about 95.4 when the channel is cleared (under 2.5 m lagoon level). This area increases in size by about 18% if the channel is vegetated.

5.4 Overall summary

Bathtub inundation modelling shows the area of land inundated by static lagoon water levels up to 2.5 m is relatively minor and generally around the mouths of the three main tributary creeks: Waituna, Moffat and Carran.

For all three Waituna, Moffat and Carran Creeks the area of land affected by direct inundation and impeded drainage is a function of lagoon level, flow rate and plant growth in the creeks. The relative importance of these three factors varies spatially. The most downstream parts of the Creeks is strongly affected by lagoon level but further upstream this has little or no effect and channel vegetation and flow dominate. For high flow, densely vegetated conditions, the lagoon level has less impact as Creek levels are already high. Under high flow conditions the area of farmland with potentially affected drainage is much higher as a result of a vegetated channel than as a result of a high lagoon level (for all three creeks).

When interpreting results from this study it is important to bear in mind the various assumptions and simplifications involved in the analysis. Of particular importance is the way simple 1 m and 2 m threshold depths to lagoon/creek water levels were applied to map the area of land potentially influenced by poor drainage, and the way varying Manning's 'n' roughness coefficients have been used to simulate vegetation. It should also be noted that study does not account for any wind effects on lagoon level.

5.5 Recommendations for further analysis

While this study provides a good basis for understanding how lagoon levels impact farmland around Waituna Lagoon there are a number of ways uncertainty could be reduced:

1. The uncertainties associated with the threshold used for mapping areas with impacted land drainage could be reduced by investigating/mapping the typical depth of field drains in low lying areas adjacent to the Creeks.

2. Further water level and flow gaugings in the identified backwater reaches under different flow and plant growth conditions would provide additional calibration/validation data to improve model certainty.

6 Acknowledgements

This study has been supported by flow, LiDAR and bathymetric data provided by Environment Southland.

7 Glossary of abbreviations and terms

ADCP	Acoustic Doppler Current Profiler: Instrument for conducting flow gaugings by measuring the distribution of flow velocity across a cross-section.
backwater	increase in creek water level due to downstream high water (lagoon level)
chainage	Distance along a river channel from the start of the modelled reach to any given cross-section
DEM	Digital Elevation Model: A digital map of land elevation
hydraulic roughness	Hydraulic roughness represents the frictional resistance of a channel to flow passing through it. In this study roughness is quantified using Manning's 'n' coefficient.
LiDAR	Abbreviation for Light Detection And Ranging. LiDAR data is high resolution topographic survey data collected using an aircraft mounted laser scanner
Manning's 'n'	Coefficient used to specify hydraulic roughness. A higher value of 'n' means the channel has more resistance so will require greater flow depths to pass a given flow. Conversely a lower 'n' means a channel will have faster shallower flow (for any given flow rate and slope). Typical values of n relevant to this study are given in Table 4-4.
raster grids	maps of data at a constant spatial resolution, for example a 20m resolution raster grid is a gridded data set where each 20m x 20m cell contains a single value.
wind set-up	Local increase in lagoon level on the downwind side of the lagoon caused by the wind inducing a sloping water surface

8 References

Chow V.T. (1959) *Open Channel Hydraulics*. McGraw-Hill, New York.

Thompson, C. (2015) Carran and Waituna Creek Cross Section Survey of Gaugings Sites. Survey Report December 2015. Report prepared by TrueSouth Survey Services Ltd., for Environment Southland, December 2015.

Appendix A Summary of metadata from flow gauging notes

Table A-1: Waituna Creek flow gauging metadata.

Location	Cross-section	Easting	Northing	Date	Start time	End time	Flow (l/s)	Details	Bed	Plant growth	Other notes
Marshall Rd Hydrology Recorder	W-8	1258125	4838490	10/12/2015	13:16	13:45	482	Pygmy, Wading	Gravel	Not really	
Marshall Rd Dairy Farm	W-6	1257775	4837589	10/12/2015	11:27	11:45	460	StreamPro, Wading	Gravel	Yes	Strong wind
Marshall Road Farm Trustee Ltd Bridge	W-5	1257745	4837288	10/12/2015	10:38	11:00	423	StreamPro, Wading	Gravel	Yes	Strong wind
500 m u/s of White Pine Rd	W-4	1257674	4836759	10/12/2015	9:43	10:04	473	StreamPro, Wading	Gravel	Yes	Moderate wind
White Pine Rd	W-3	1257842	4836348	10/12/2015	8:45	8:59	465	StreamPro, Wading	Gravel	Yes	
500 m d/s White Pine Rd	W-2	1258032	4835904	10/12/2015	8:02	8:19	495	StreamPro, Wading	Gravel	Not really	
1000 m d/s White Pine Rd	W-1	1258120	4835345	10/12/2015	7:19	7:32	541	StreamPro, Wading	Gravel	No	

Table A-2: Carran Creek flow gauging metadata.

Location	Cross-section	Easting	Northing	Date	Start time	End time	Flow (l/s)	Details	Bed	Plant growth	Other notes
1500 m u/s of Waituna Lagoon Rd	C-7	1267302	4837462	9/12/2015	16:53	17:18	90	StreamPro, Wading	Muddy	Very weedy[1]	Difficult to get consistent flows. Lots of sweet grass
1000 m u/s of Waituna Lagoon Rd	C-6	1267027	4837081	9/12/2015	15:38	16:05	116	StreamPro, Wading	Muddy	Choked with weeds except for narrow channel	Stage dropped 3mm while on site. Site d/s of hydrology recorder
500 m u/s of Waituna Lagoon Rd	C-5	1266664	4836756	9/12/2015	14:01	14:30	138	StreamPro, Wading	Gravel/Muddy	Very Weedy	
Waituna Lagoon Rd Bridge	C-4	1266566	4836441	9/12/2015	9:10	9:57	175	StreamPro, Wading	Gravel	Only on sides in clumps	
650 m d/s of Waituna Lagoon Rd	C-3	1266777	4835976	9/12/2015	11:54	12:09	156	StreamPro, Wading	Sand/Gravel	Very Weedy	
800 m d/s of Waituna Lagoon Rd	C-2	1266790	4835845	9/12/2015	11:13	11:21	187	StreamPro, Wading	Sand/Gravel	Very Weedy	
Outflow to Little Lake Waituna	C-1	1266935	4835657	9/12/2015	10:58	11:01	48	StreamPro, Boat	Sand/Gravel	Slightly	Unsuitable site - flow only rough estimate from 1 crossing

1. "Weedy" in the hydraulic sense is used to refer to plants blocking the flow and does not imply invasive/alien species.

Table A-3: Moffat Creek flow gauging metadata.

Location	Cross-section	Easting	Northing	Date	Start time	End time	Flow (l/s)	Details	Bed	Plant growth	Other notes
Tributary, upstream of Moffat Rd	M-8	1260941	4836654	8/3/2017	17:07	18:08	17	Ott, Wading		Very weedy	shallow but straight section with expected velocity patterns
u/s of Hansen Rd	M-7	1260693	4837401	8/3/2017	15:50	16:20	28	Ott, Wading		Extremely weed choked	Upon arrival the stream was not flowing. Straight section with slow velocity
500 m u/s Moffat Rd	M-6	1260480	4836907	8/3/2017	14:07	14:41	24	Ott, Wading	Gravel	Very weedy	Shallow creek, straight section
Moffat Creek at Moffat Rd	M-5	1260364	4836402	1/3/2017	08:26	09:01	47	Ott, Wading	Sand/gravel	Relatively weed free	Straight section, ex Hydrology site for ES
300 m d/s Moffat Rd	M-4A	1260115	4836234	1/3/2017	15:26	16:01	54	Ott, Wading	Gravel	Very weedy	Constricted stream, relatively straight section
1150 m d/s Moffatt Rd (100 m u/s survey site 3)	M-3A	1259576	4835753	1/3/2017	14:12	14:47	60	Ott, Wading	Gravel	Weedy creek	Relatively straight section
2 km d/s Moffat Rd	M-2	1259480	4835048	1/3/2017	12:30	13:30	86	Ott, Wading	Gravel	Whole creek is very weedy	Tile drain upstream discharging
600 m from lagoon	M-1A	1259626	4834728	1/3/2017	10:37	11:36	121	Ott, Wading	Gravel	Not too weedy	Deep and slow velocity (especially in bottom measurement)

Appendix B Waituna Creek inundation extent maps

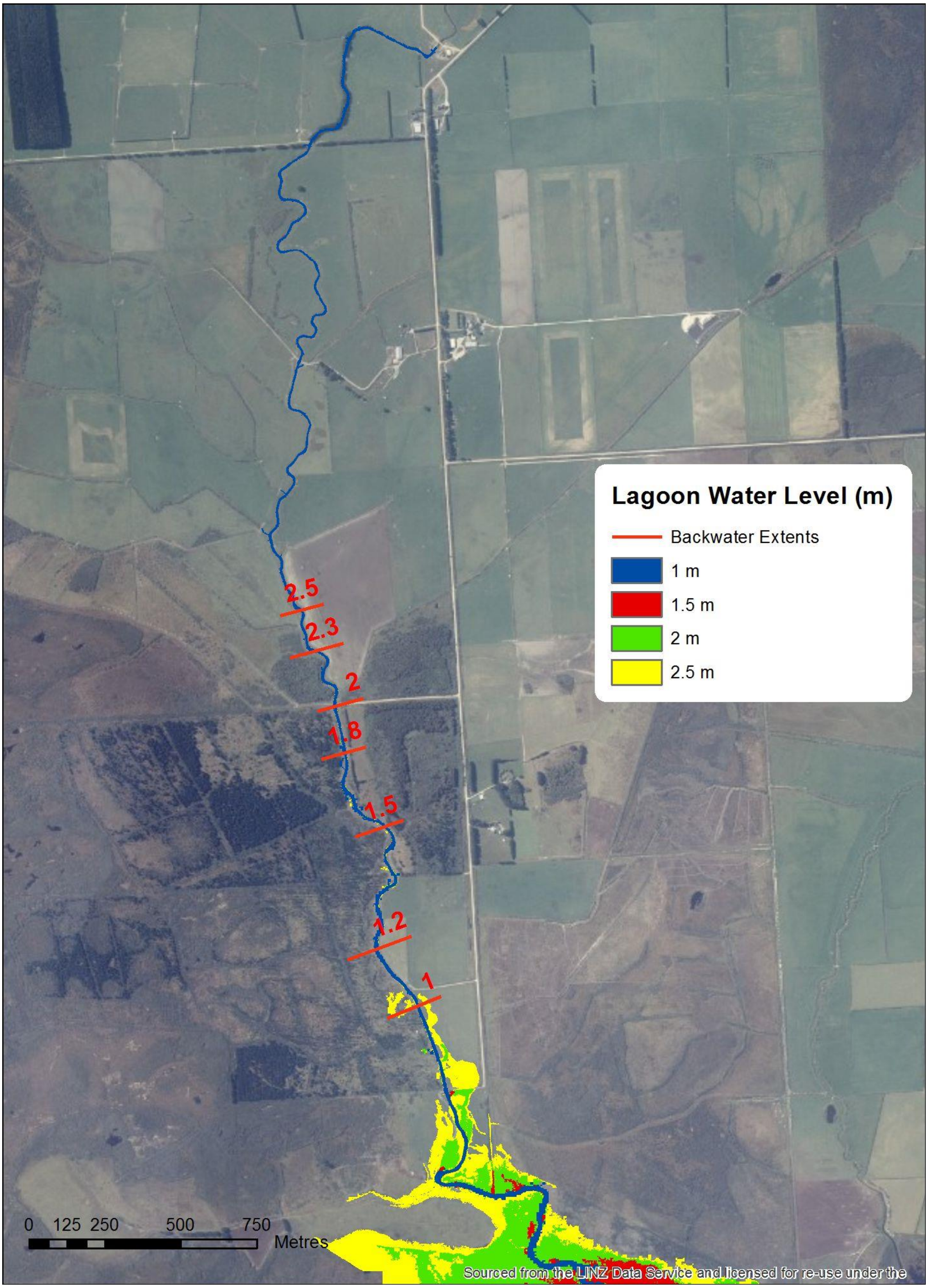

Figure B-1: Extent of Inundated land from Waituna Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Cleared". Inundated land is mapped for lagoon water levels of 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

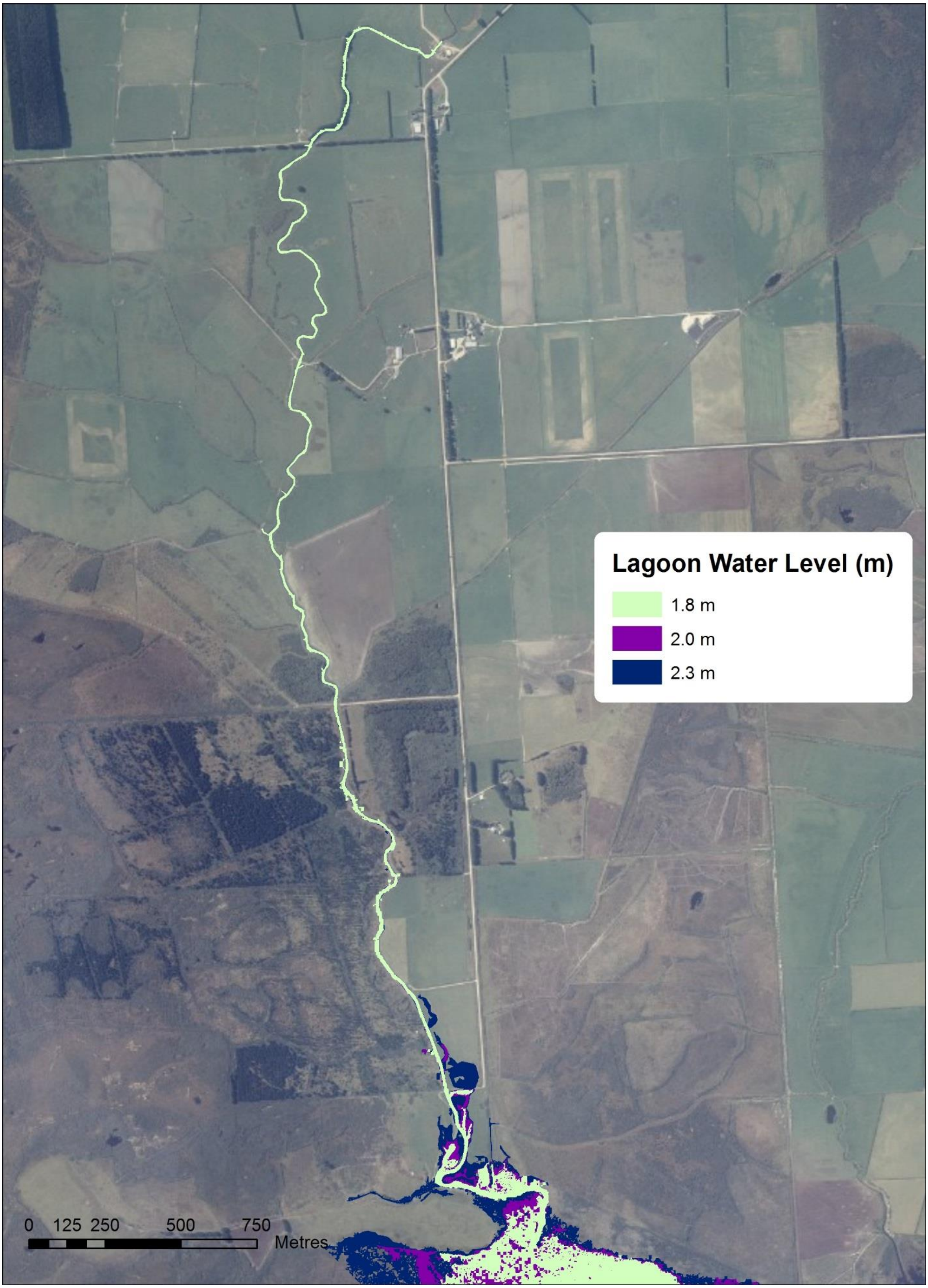

Figure B-2: Extent of Inundated land from Waituna Creek for scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

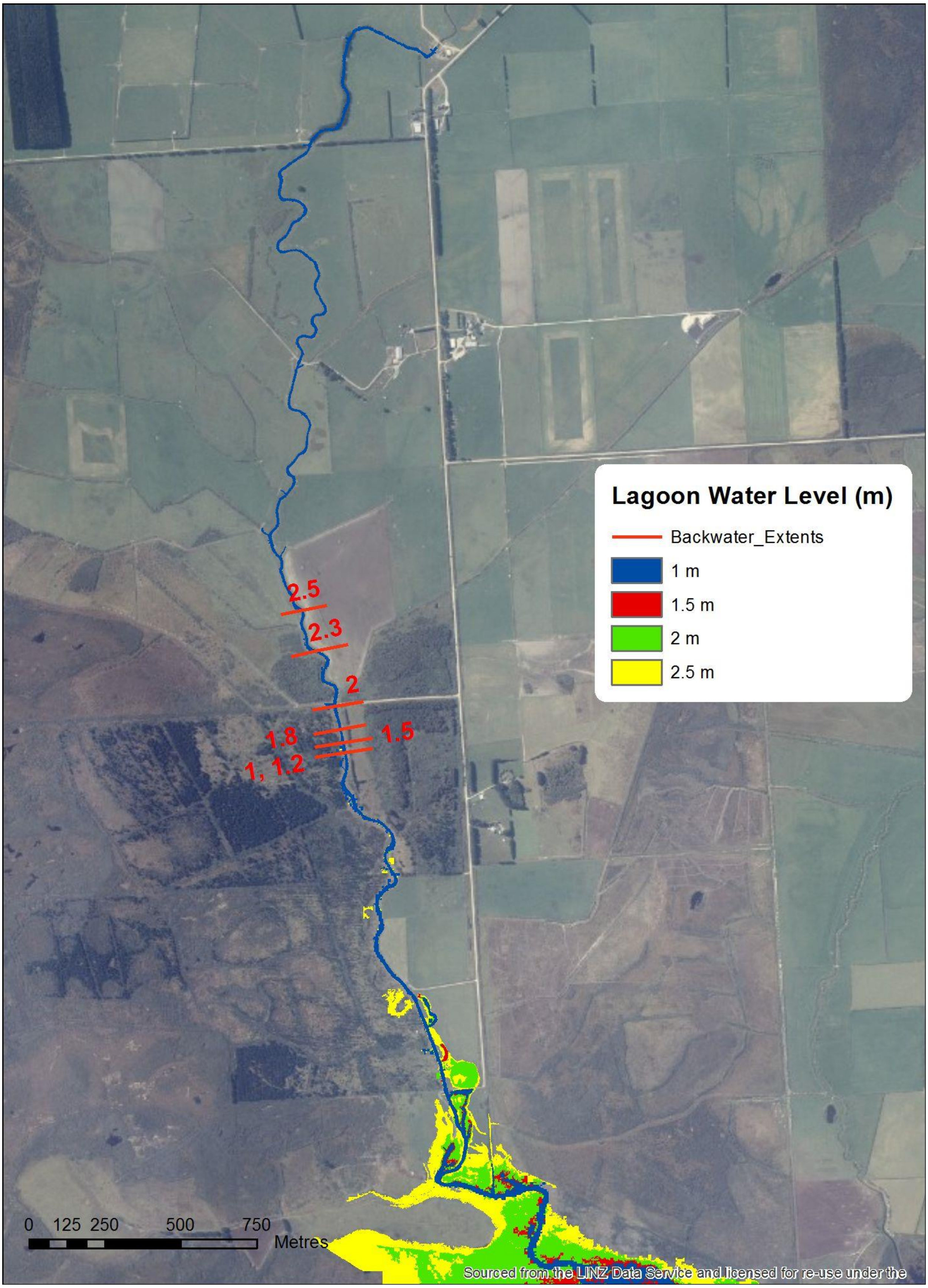

Figure B-3: Extent of Inundated land from Waituna Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Cleared". Inundated land is mapped for lagoon water levels of 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

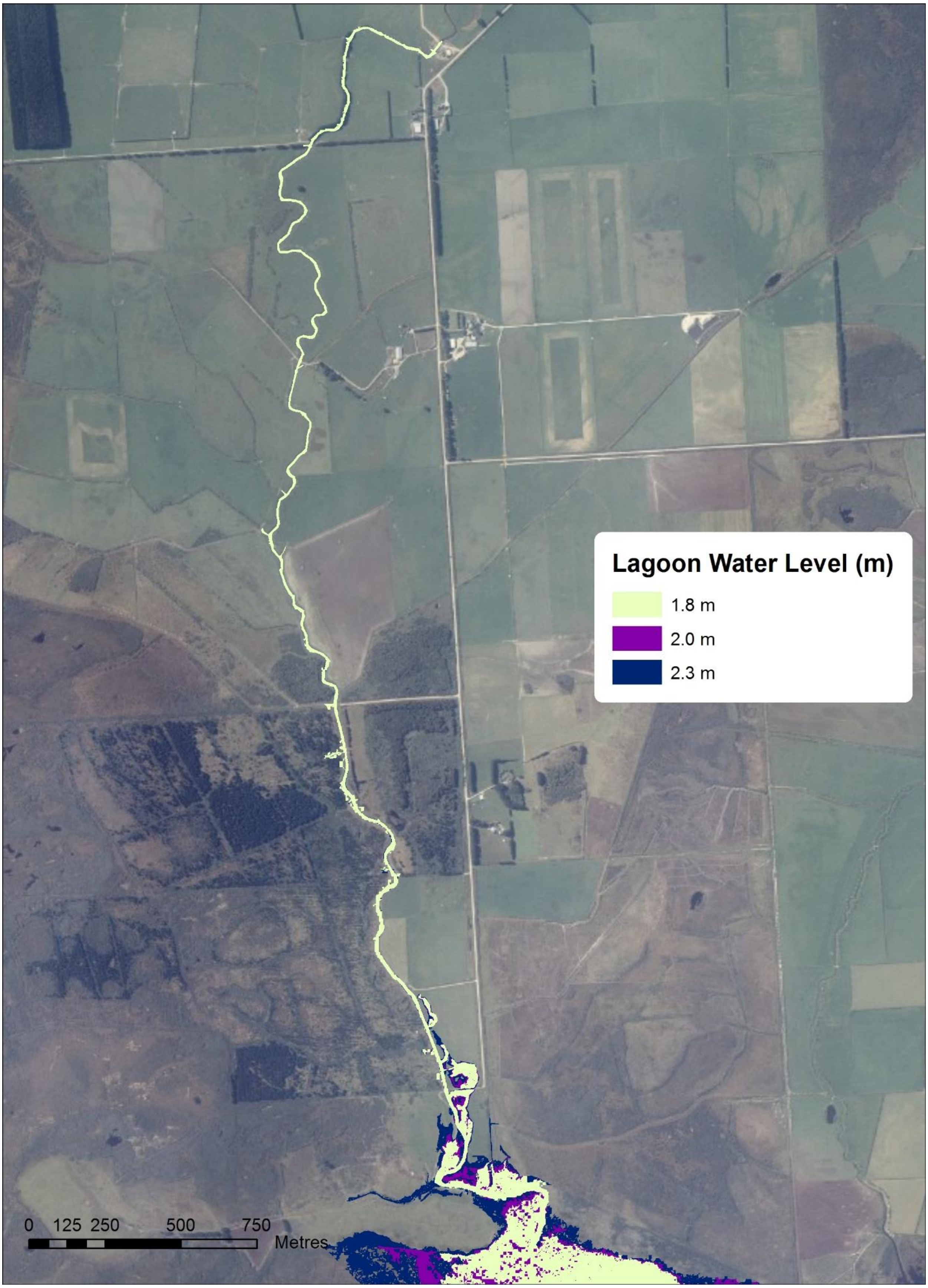

Figure B-4: Extent of Inundated land from Waituna Creek for scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

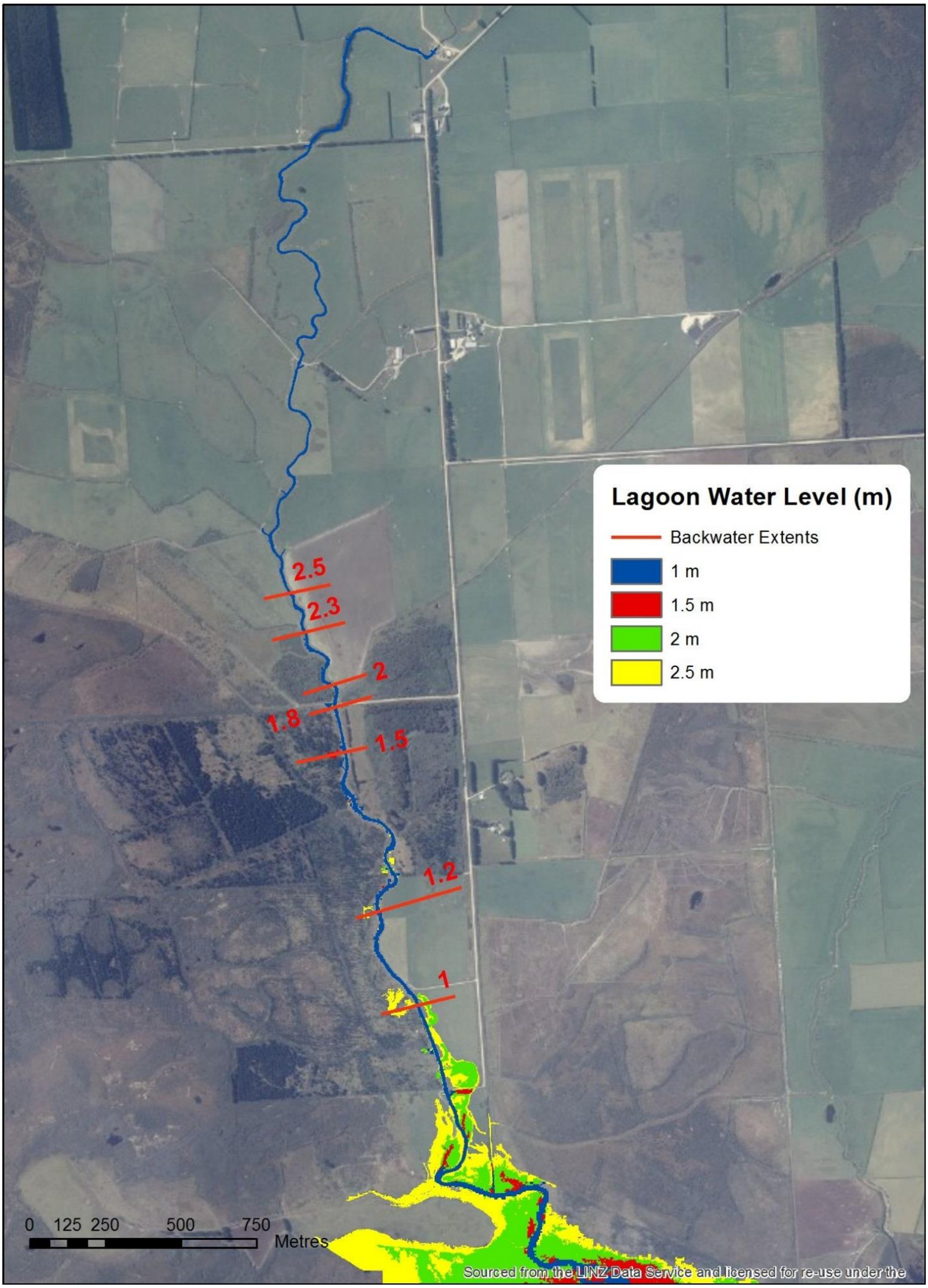

Figure B-5: Extent of Inundated land from Waituna Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

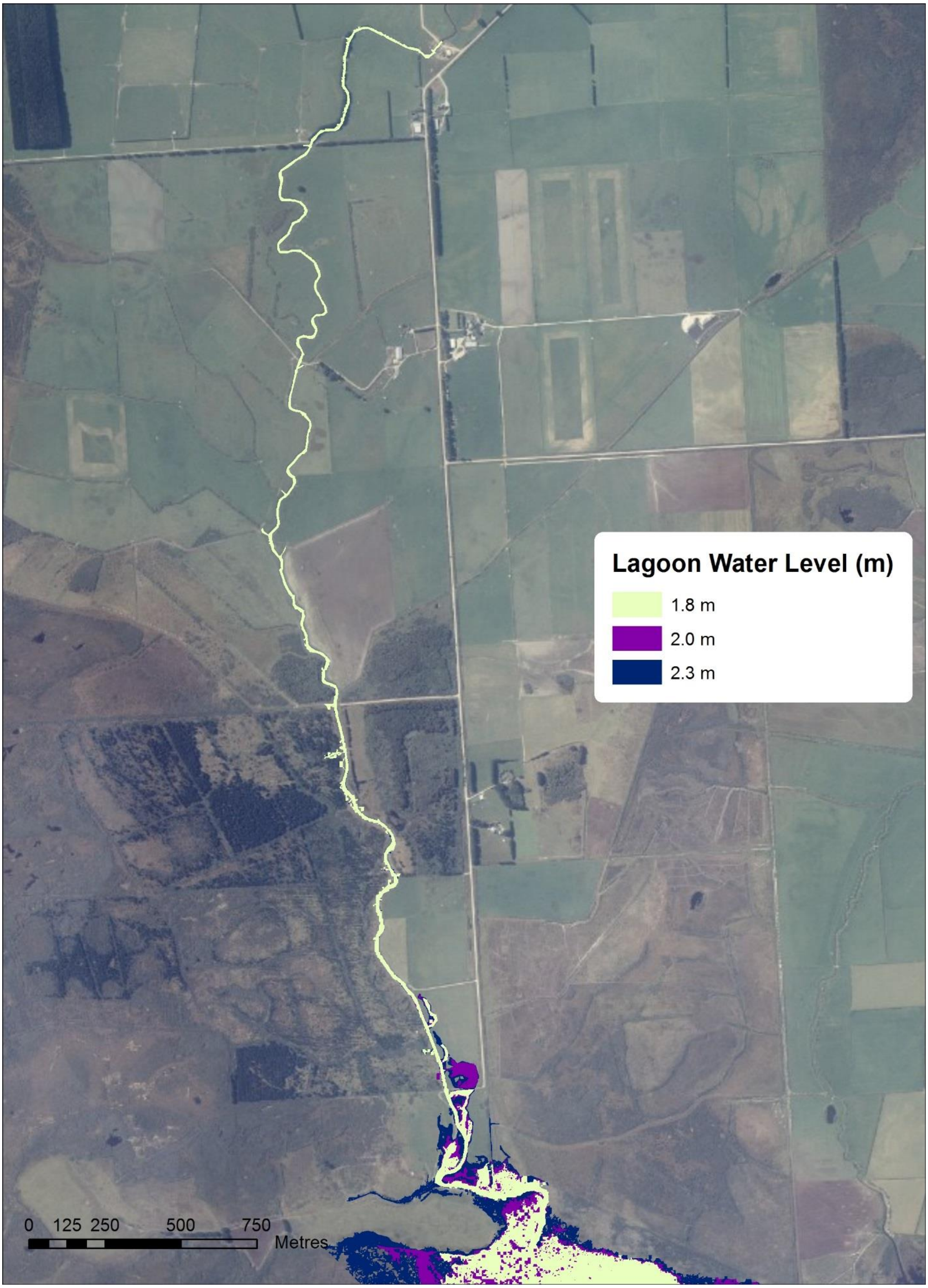

Figure B-6: Extent of Inundated land from Waituna Creek for scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

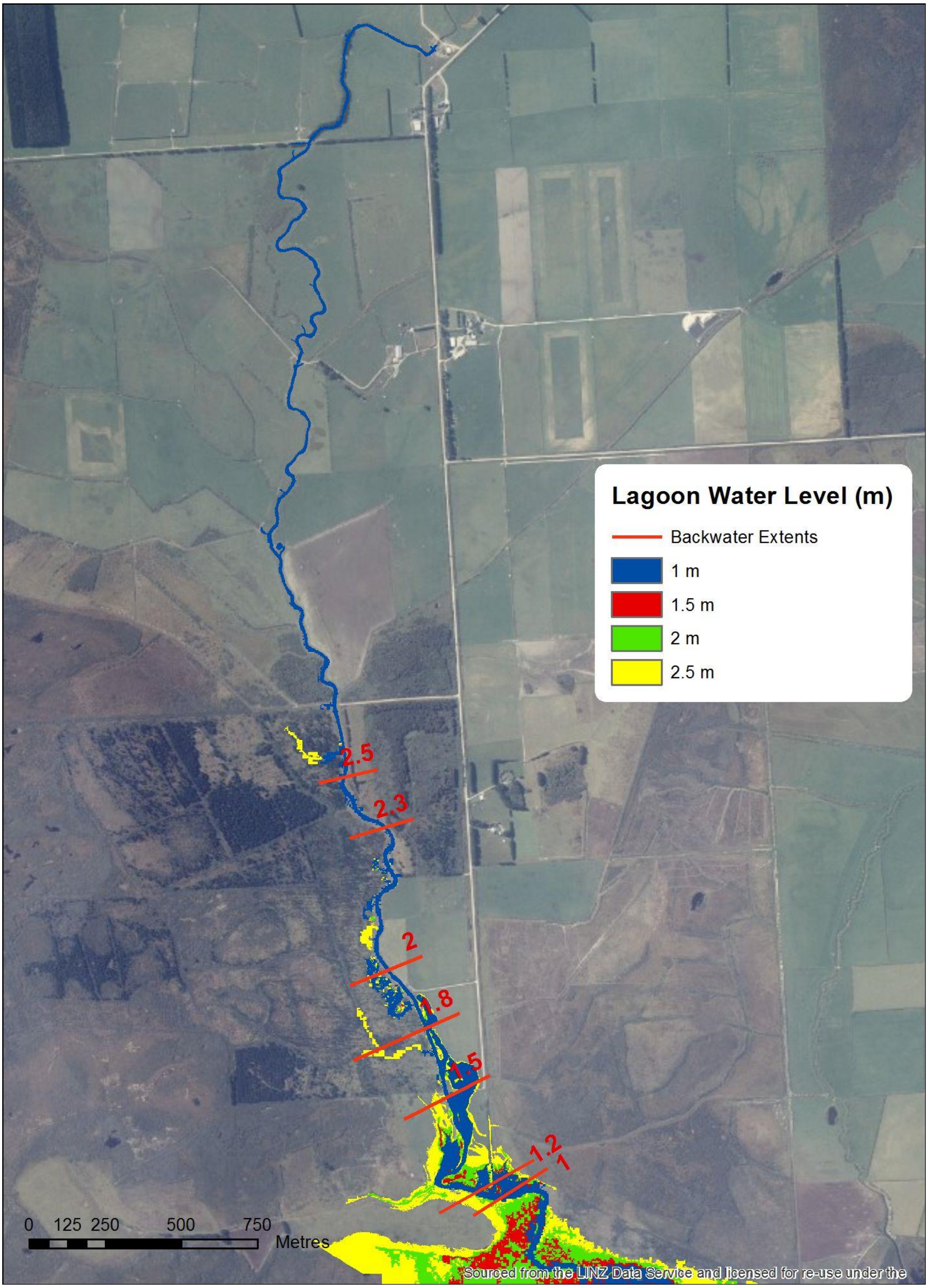

Figure B-7: Extent of Inundated land from Waituna Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

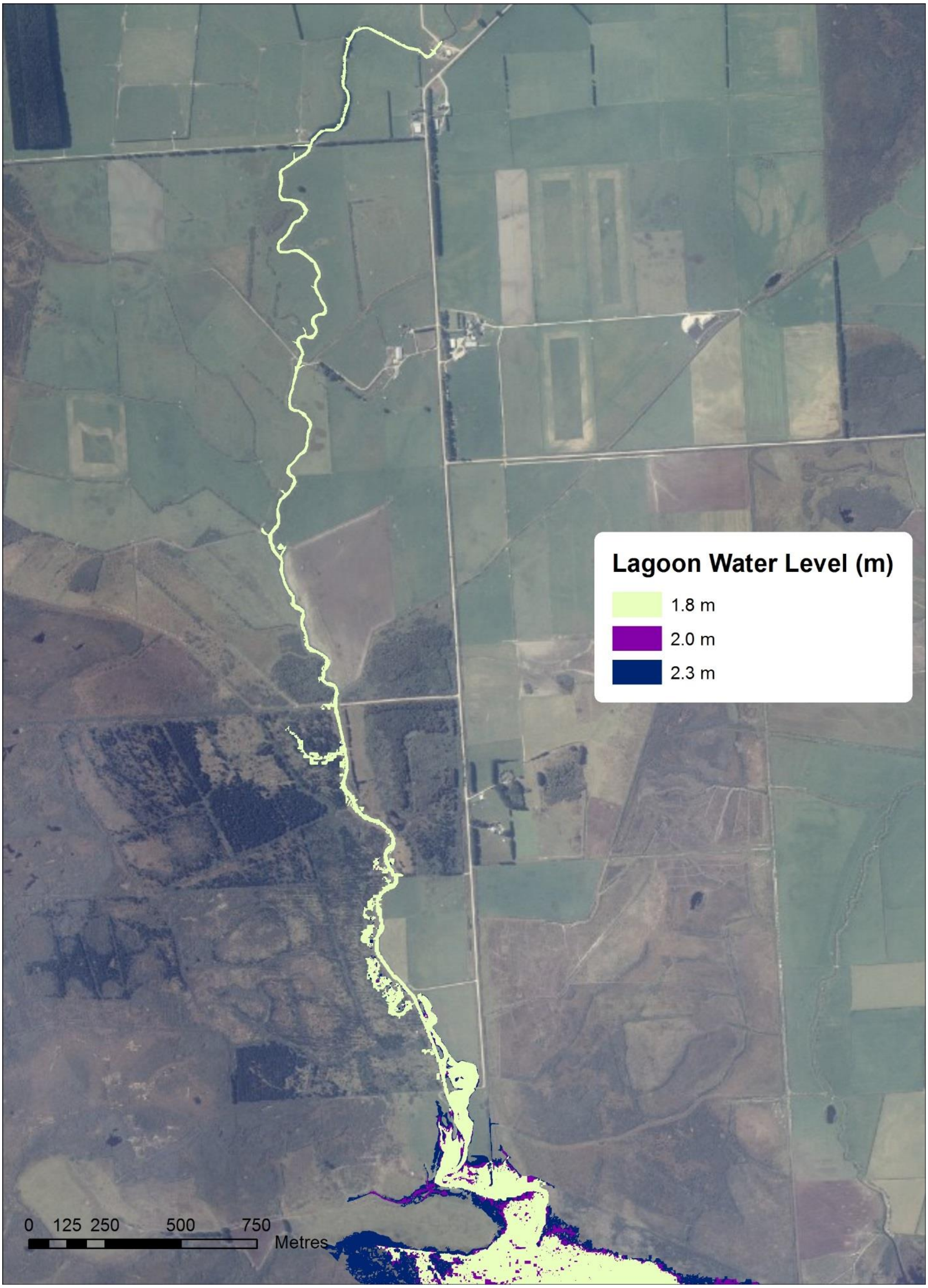

Figure B-8: Extent of Inundated land from Waituna Creek for scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

Appendix C Moffat Creek inundation extent maps

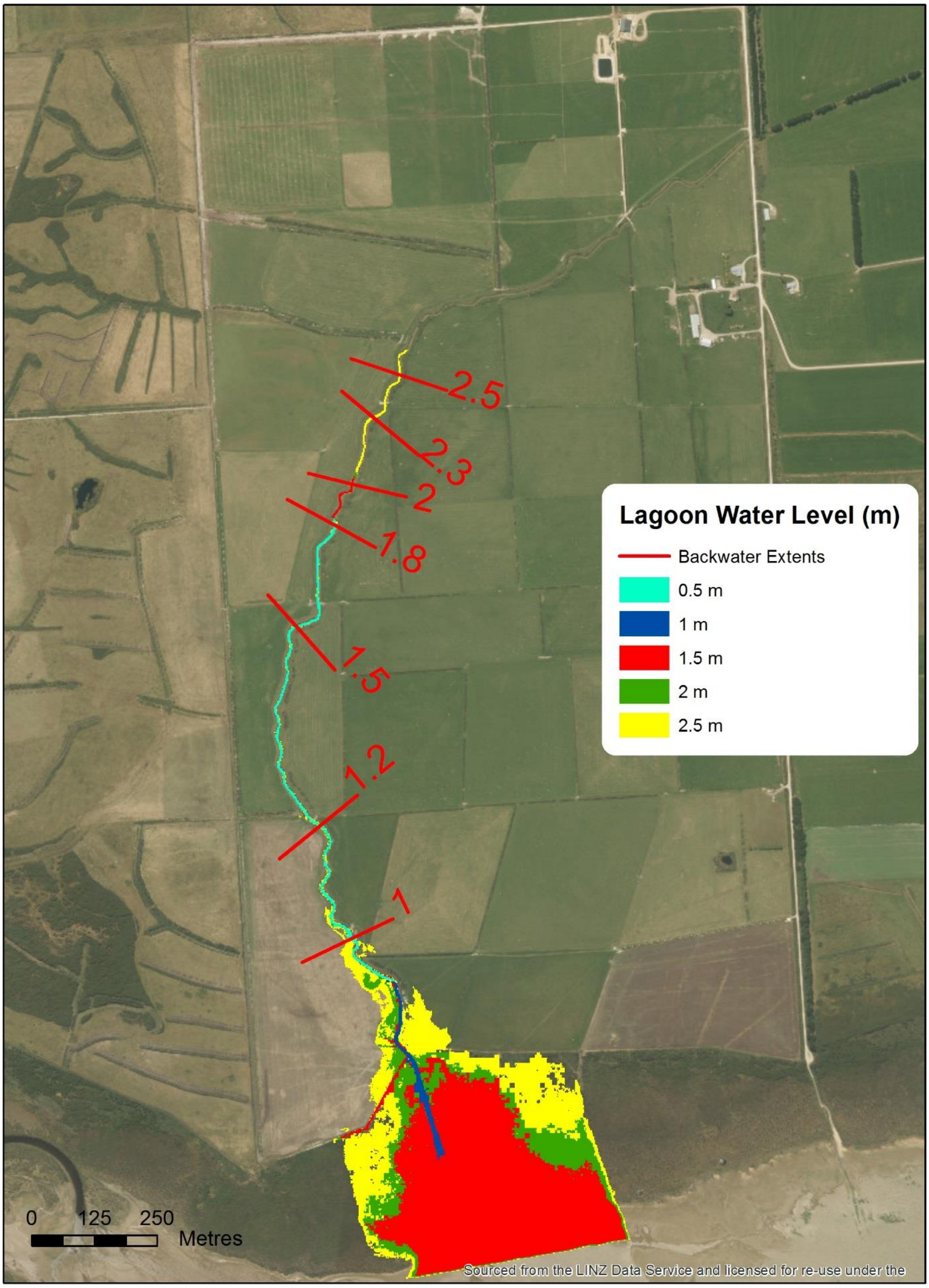

Figure C-1: Extent of Inundated land from Moffat Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Cleared". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

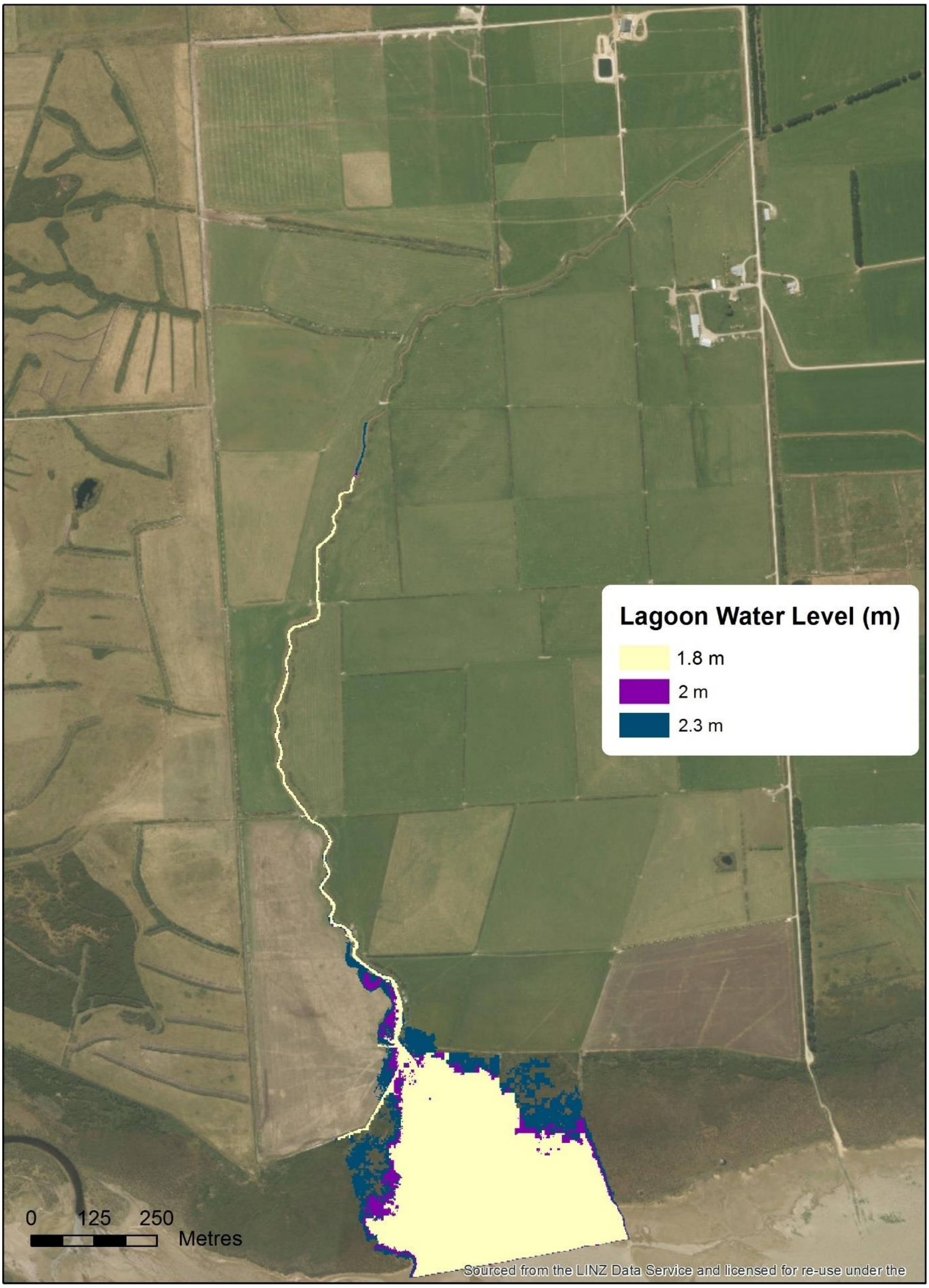

Figure C-2: Extent of Inundated land from Moffat Creek for scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

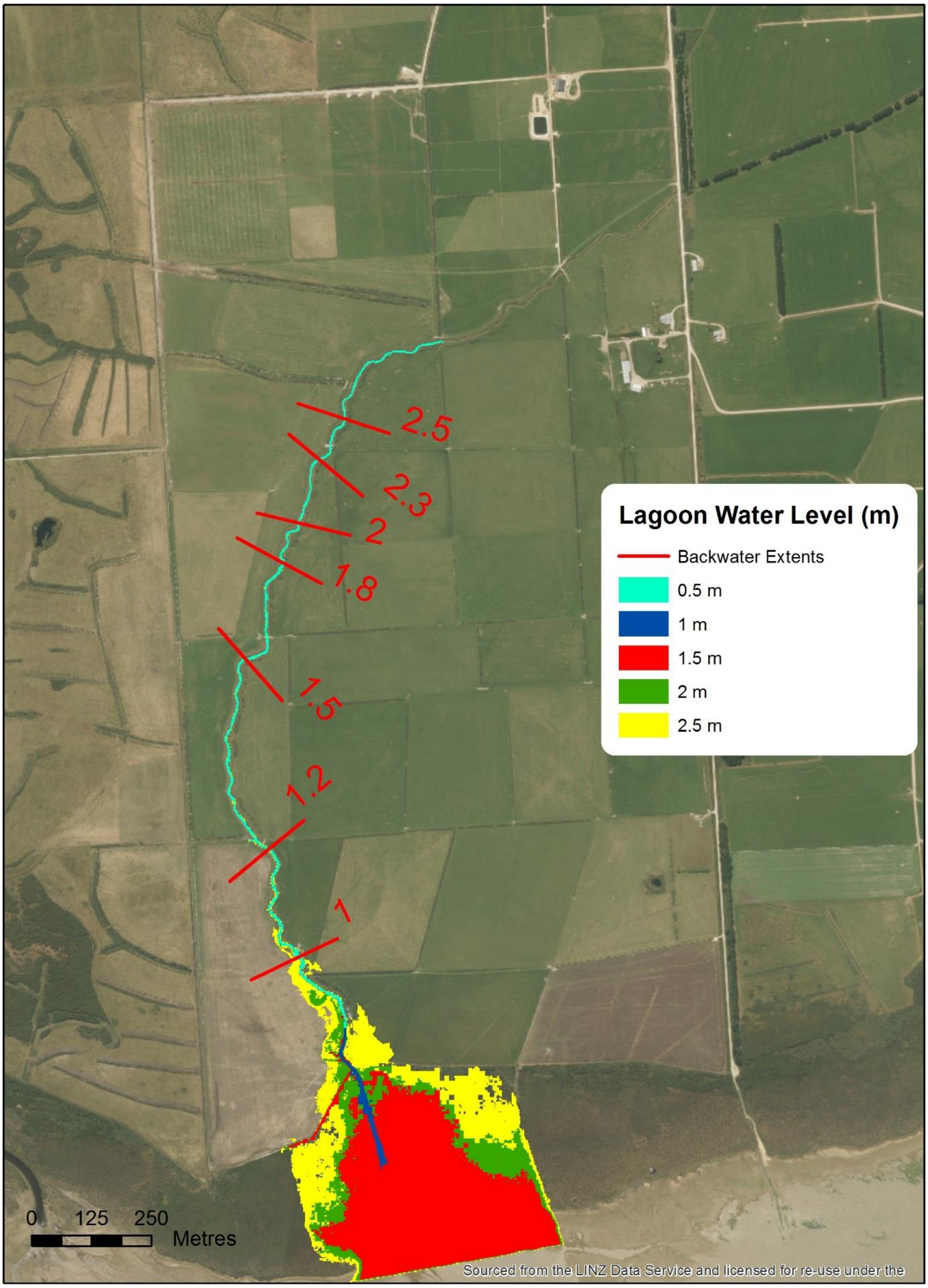

Figure C-3: Extent of Inundated land from Moffat Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Cleared". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

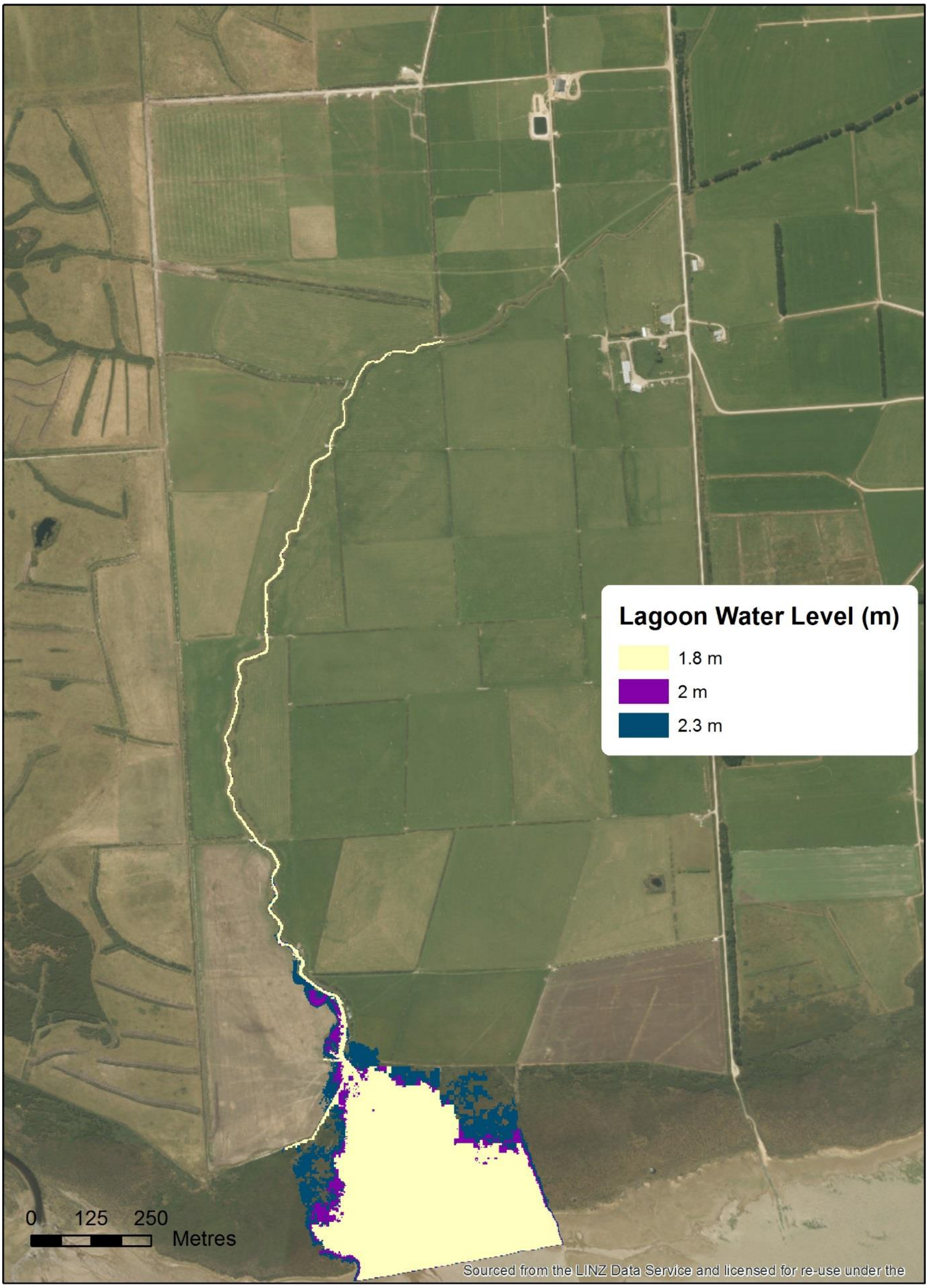

Figure C-4: Extent of Inundated land from Moffat Creek for scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 0.5 m, 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

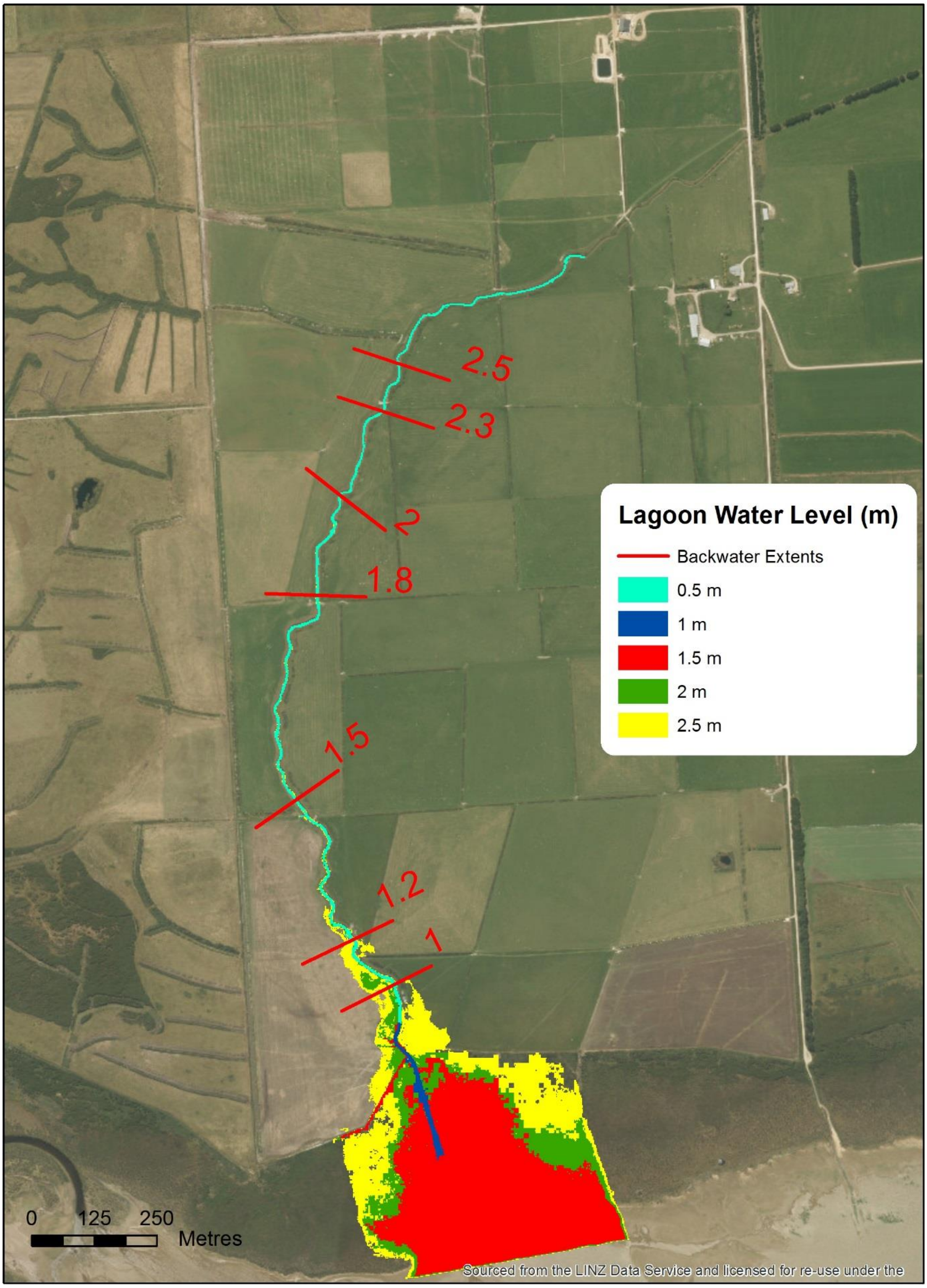

Figure C-5: Extent of Inundated land from Moffat Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

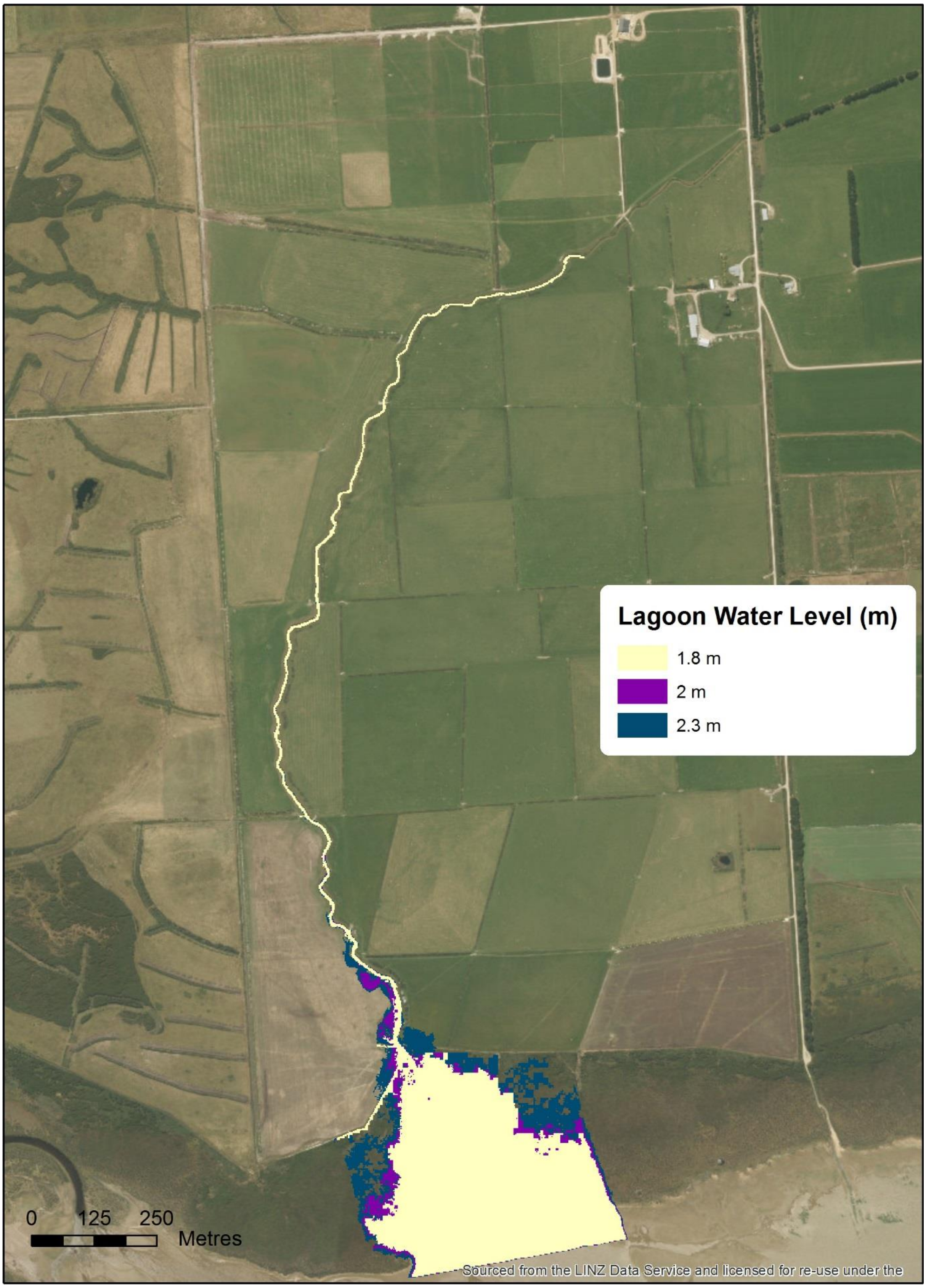

Figure C-6: Extent of Inundated land from Moffat Creek for scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

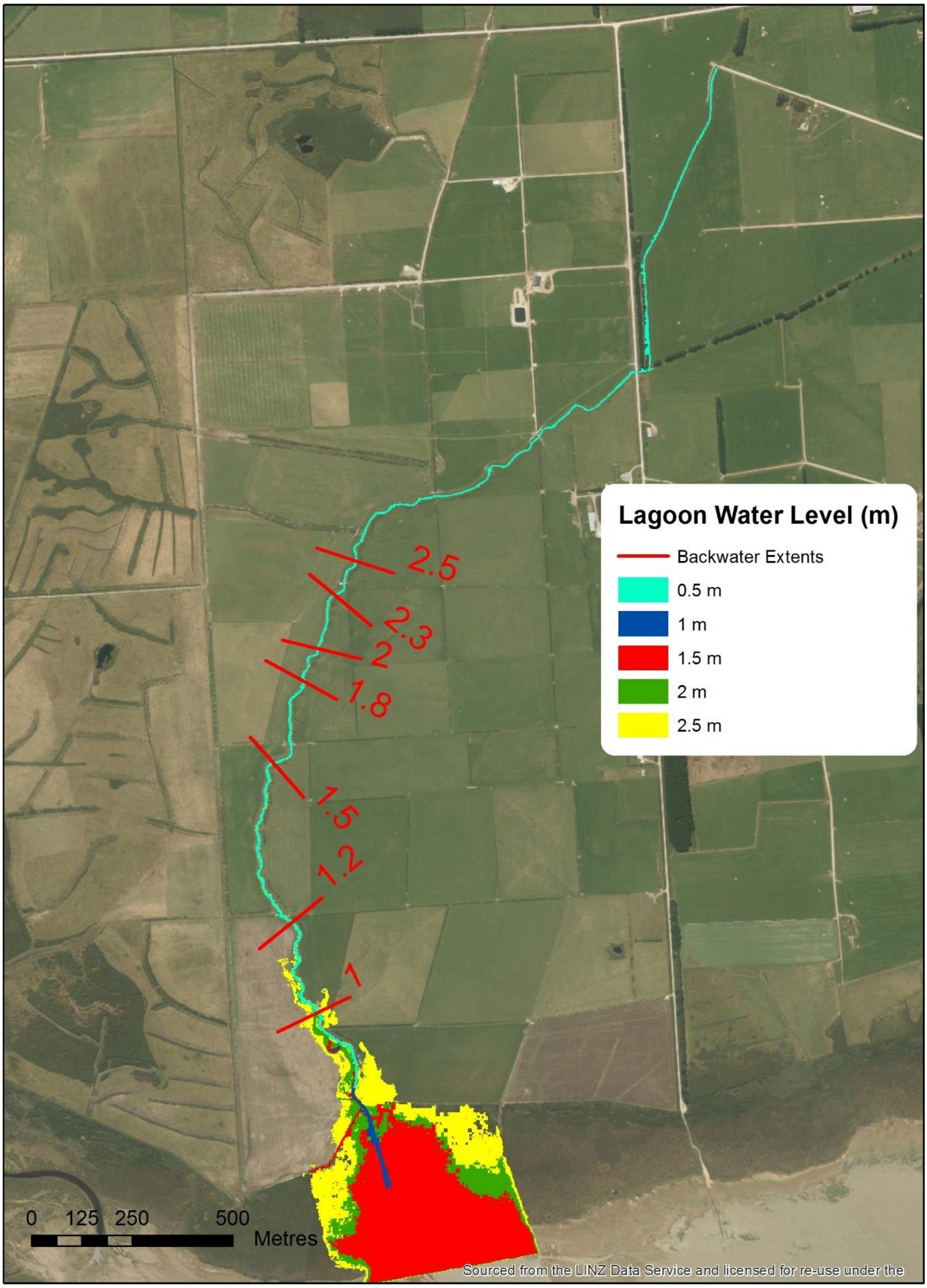

Figure C-7: Extent of Inundated land from Moffat Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

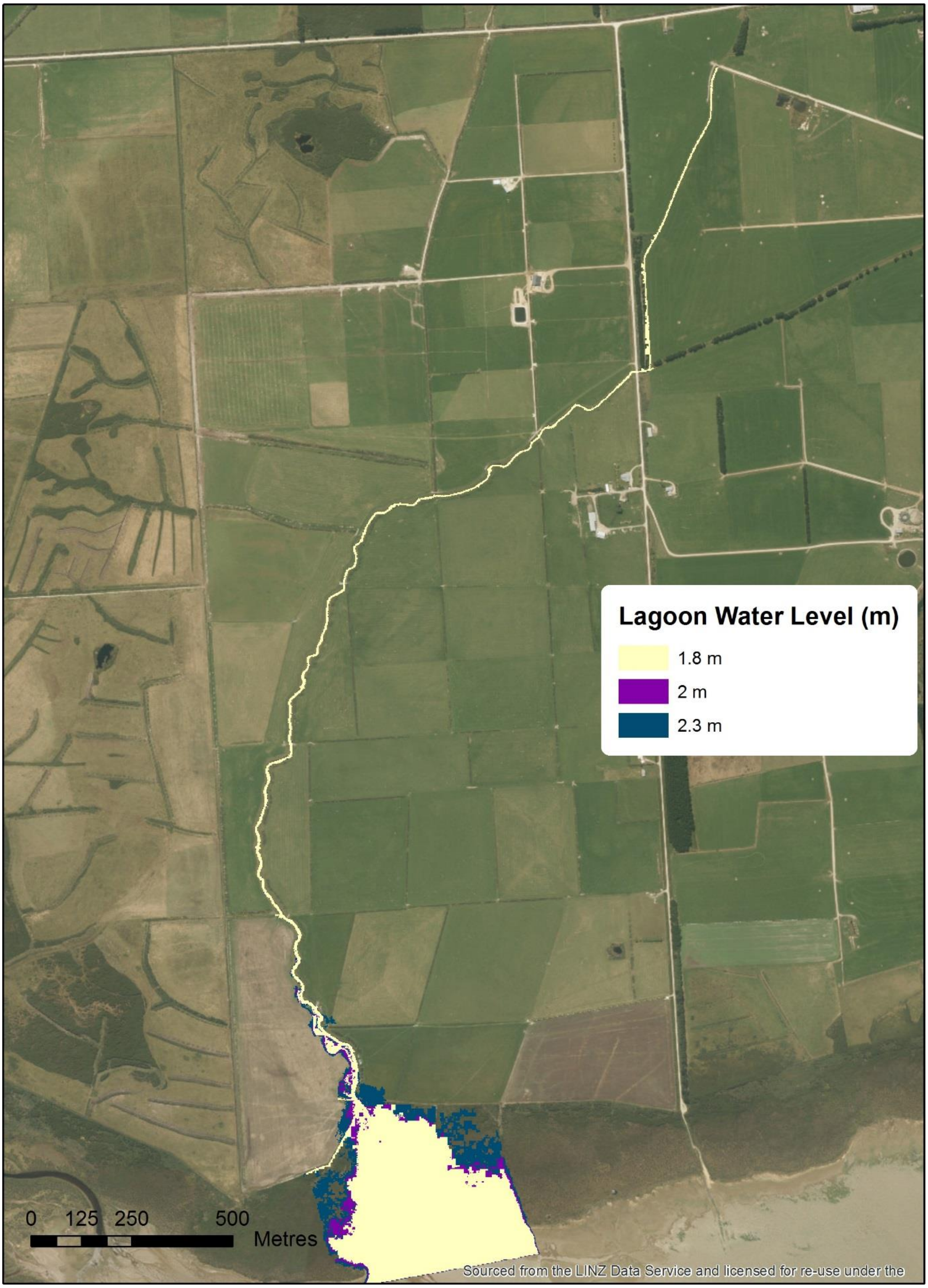

Figure C-8: Extent of Inundated land from Moffat Creek for scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

Appendix D Carran Creek inundation extent maps

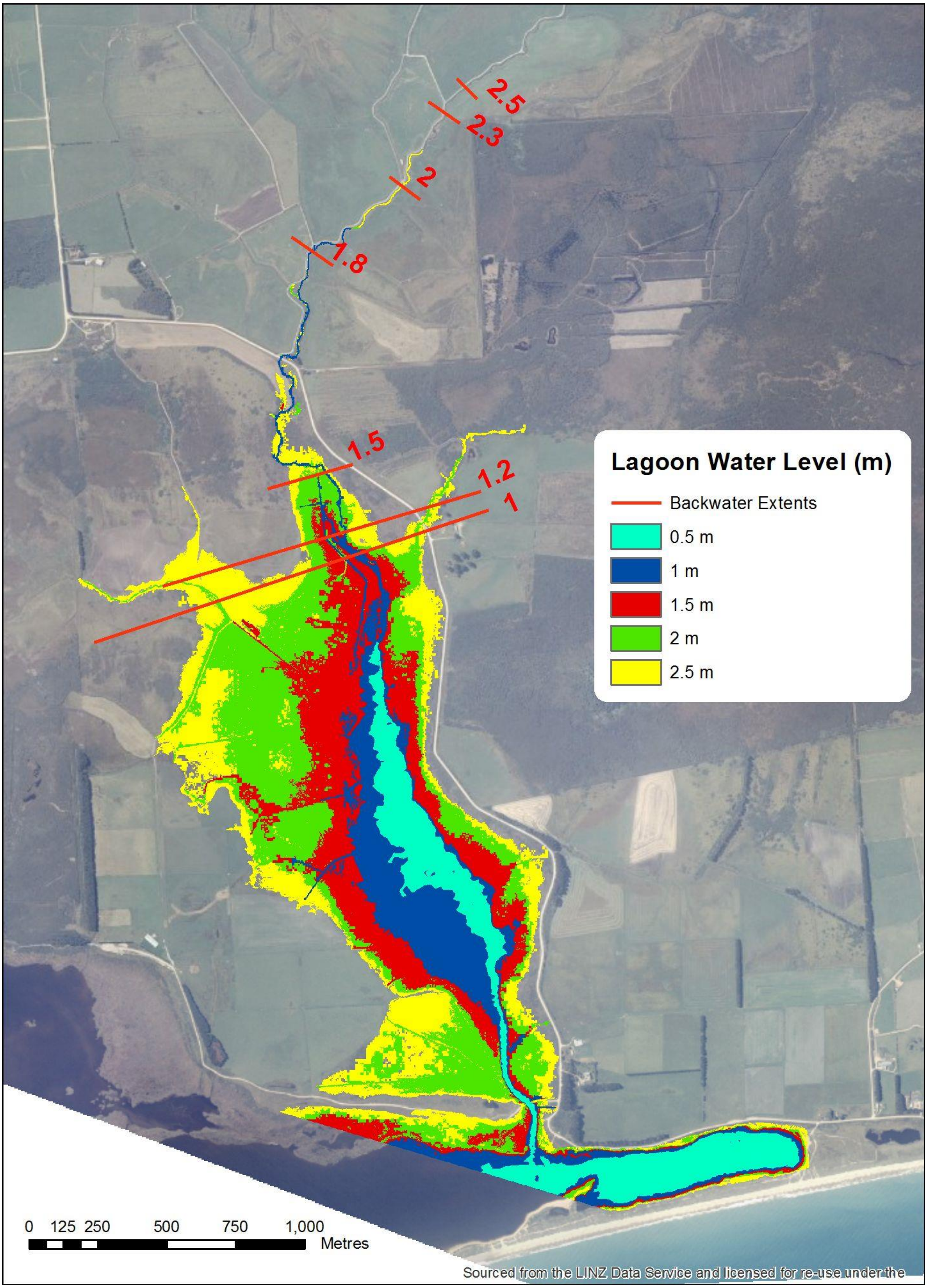

Figure D-1: Extent of Inundated land from Carran Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Cleared". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

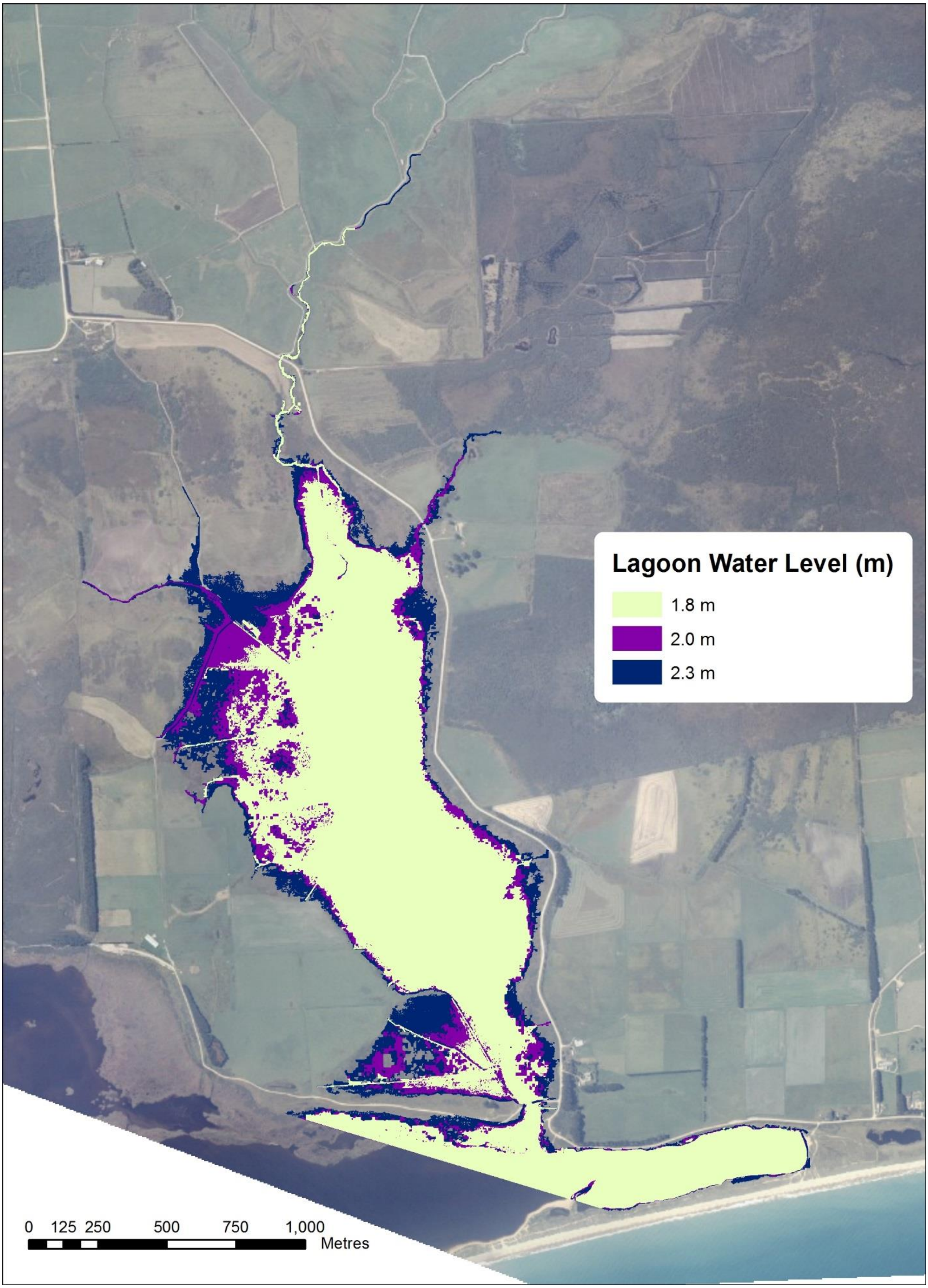

Figure D-2: Extent of Inundated land from Carran Creek for scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

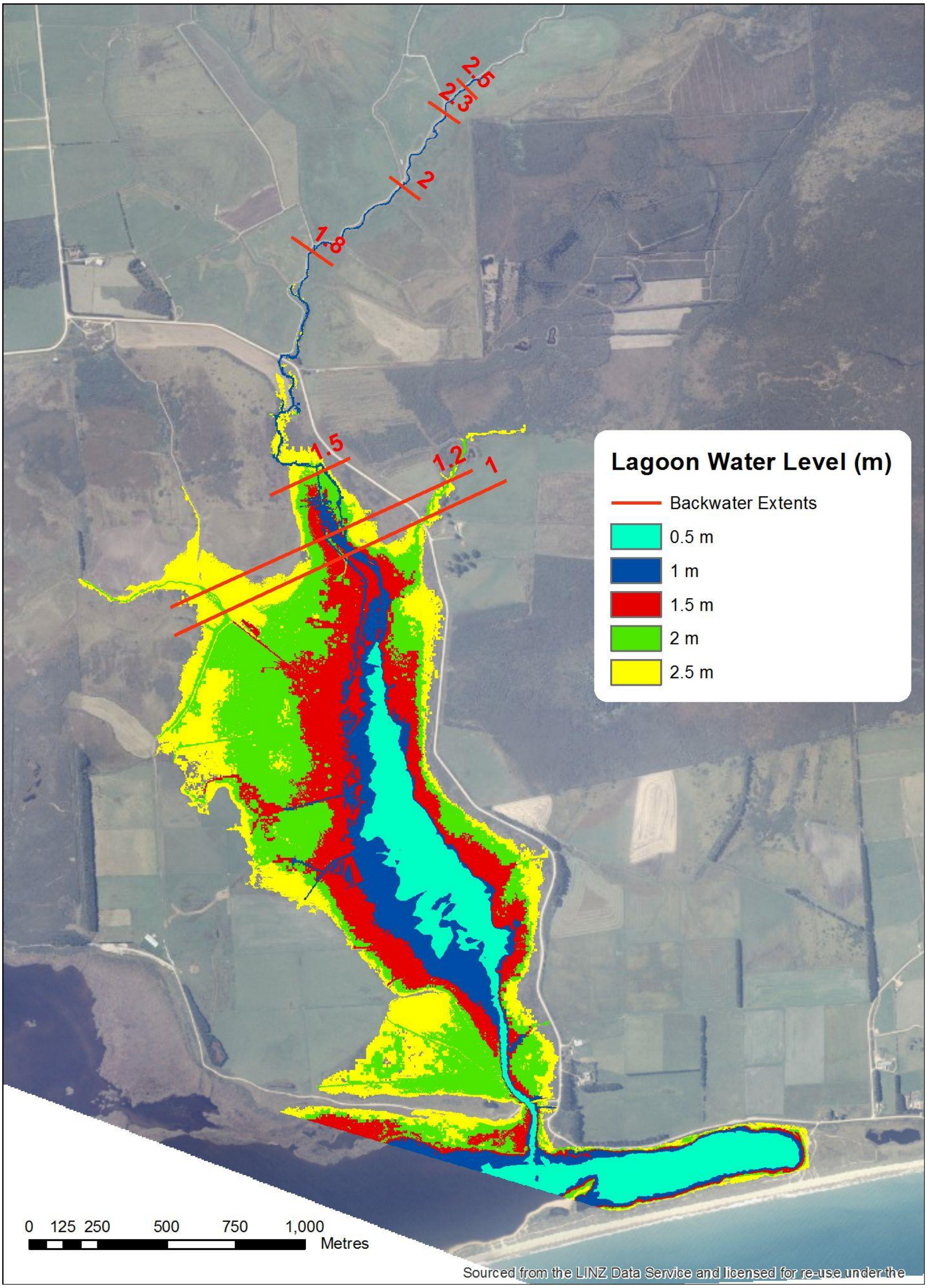

Figure D-3: Extent of Inundated land from Carran Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Cleared". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

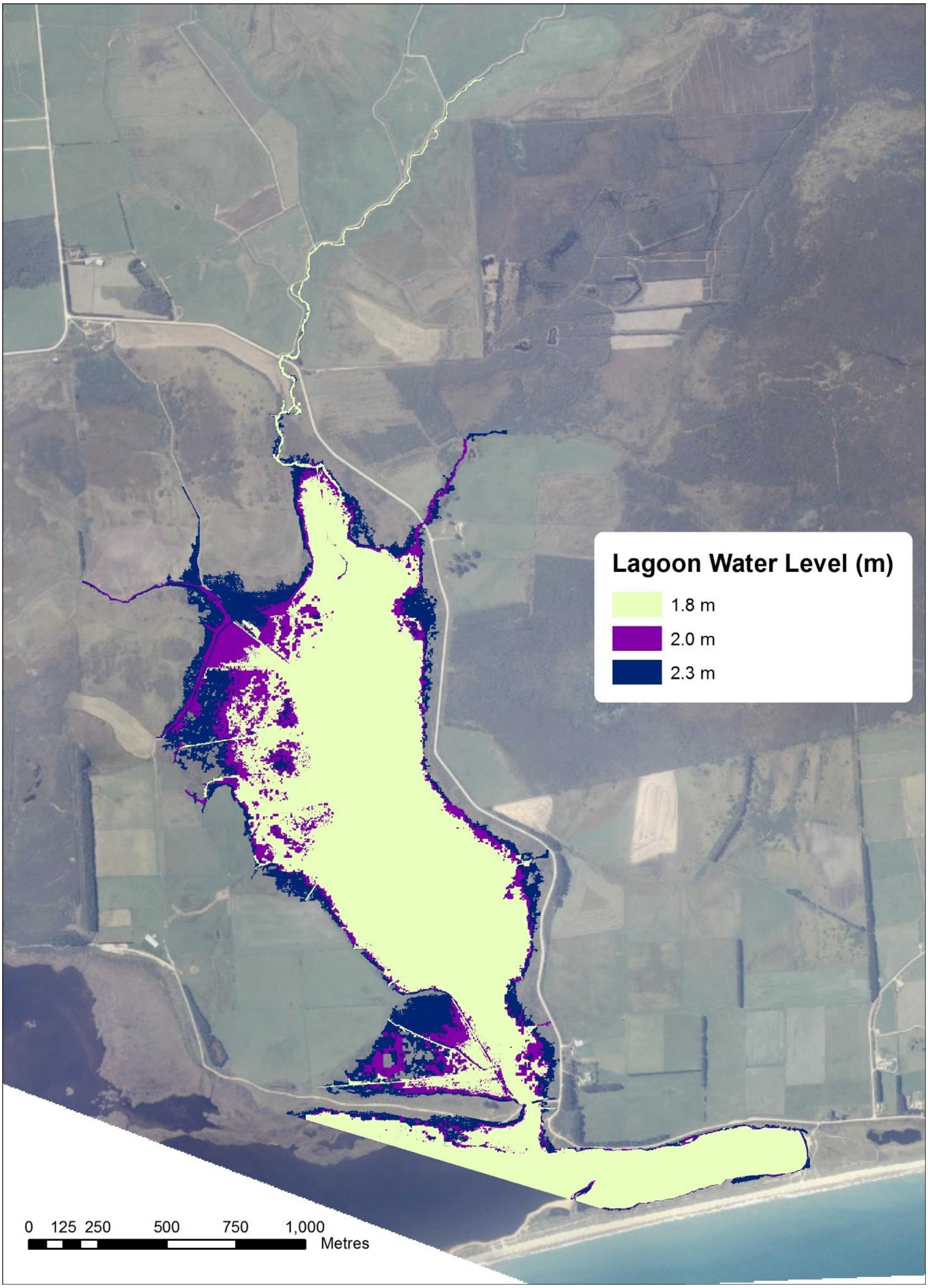

Figure D-4: Extent of Inundated land from Carran Creek for scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

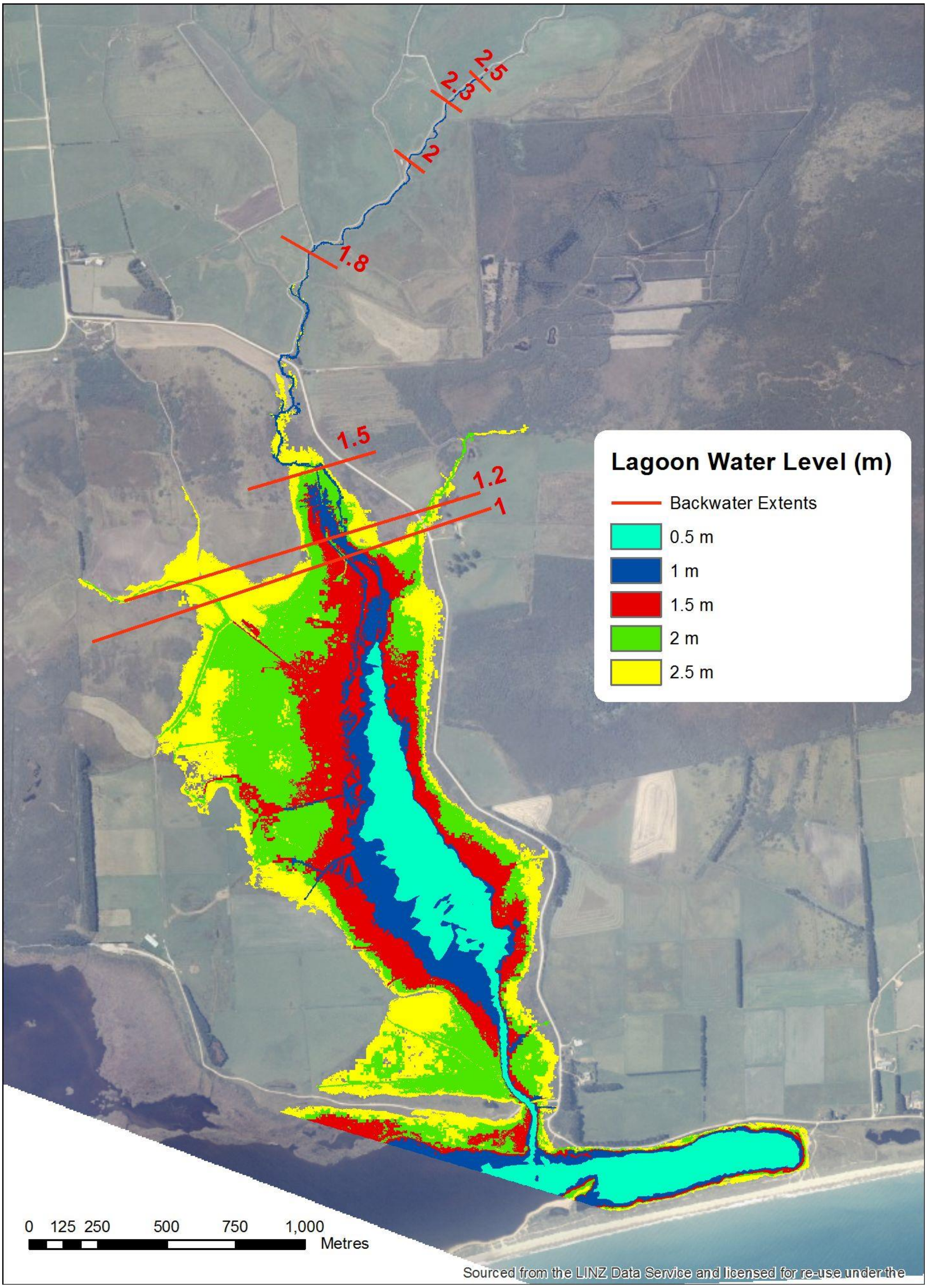

Figure D-5: Extent of Inundated land from Carran Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{mean}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

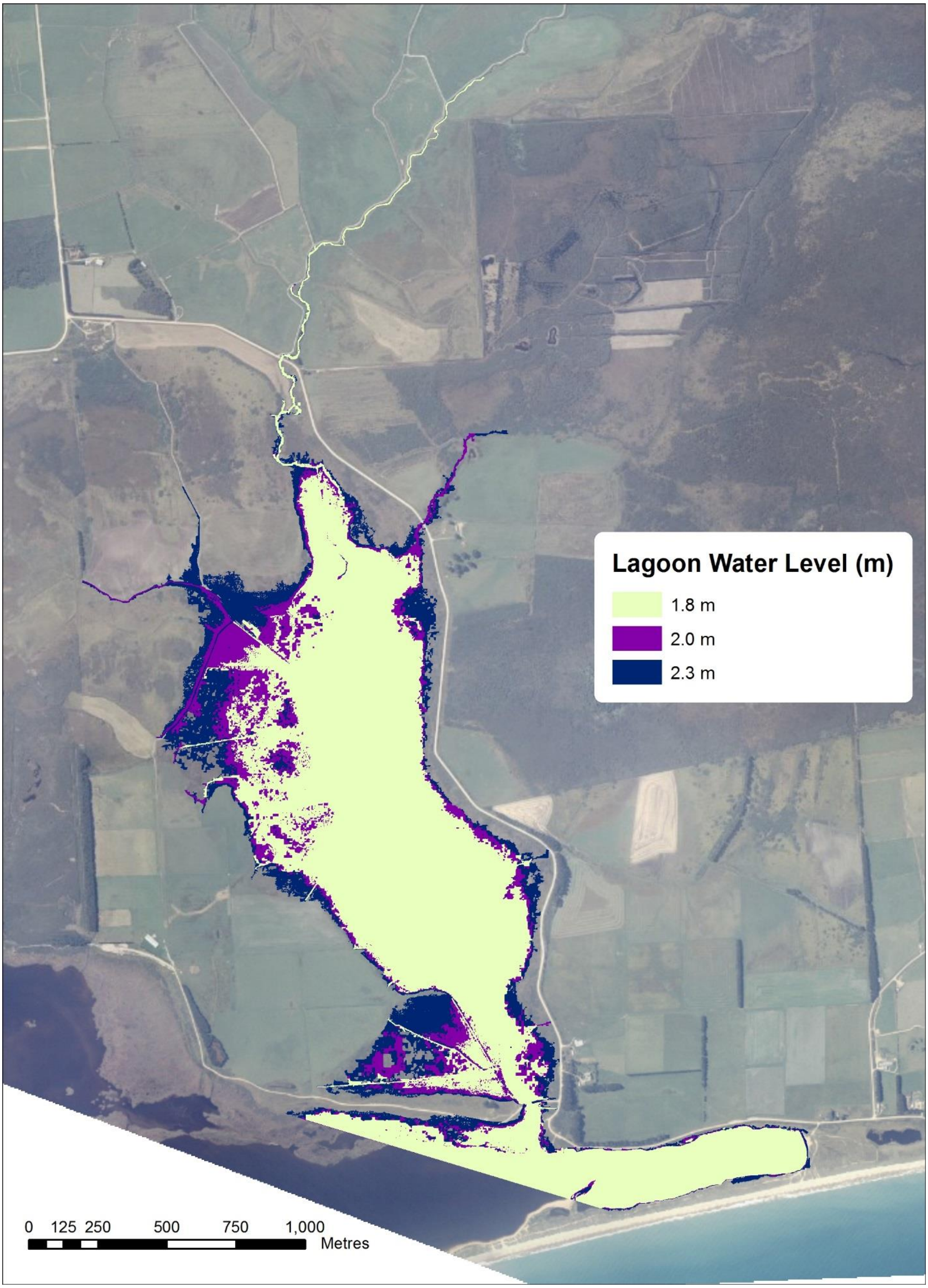

Figure D-6: Extent of Inundated land from Carran Creek for scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

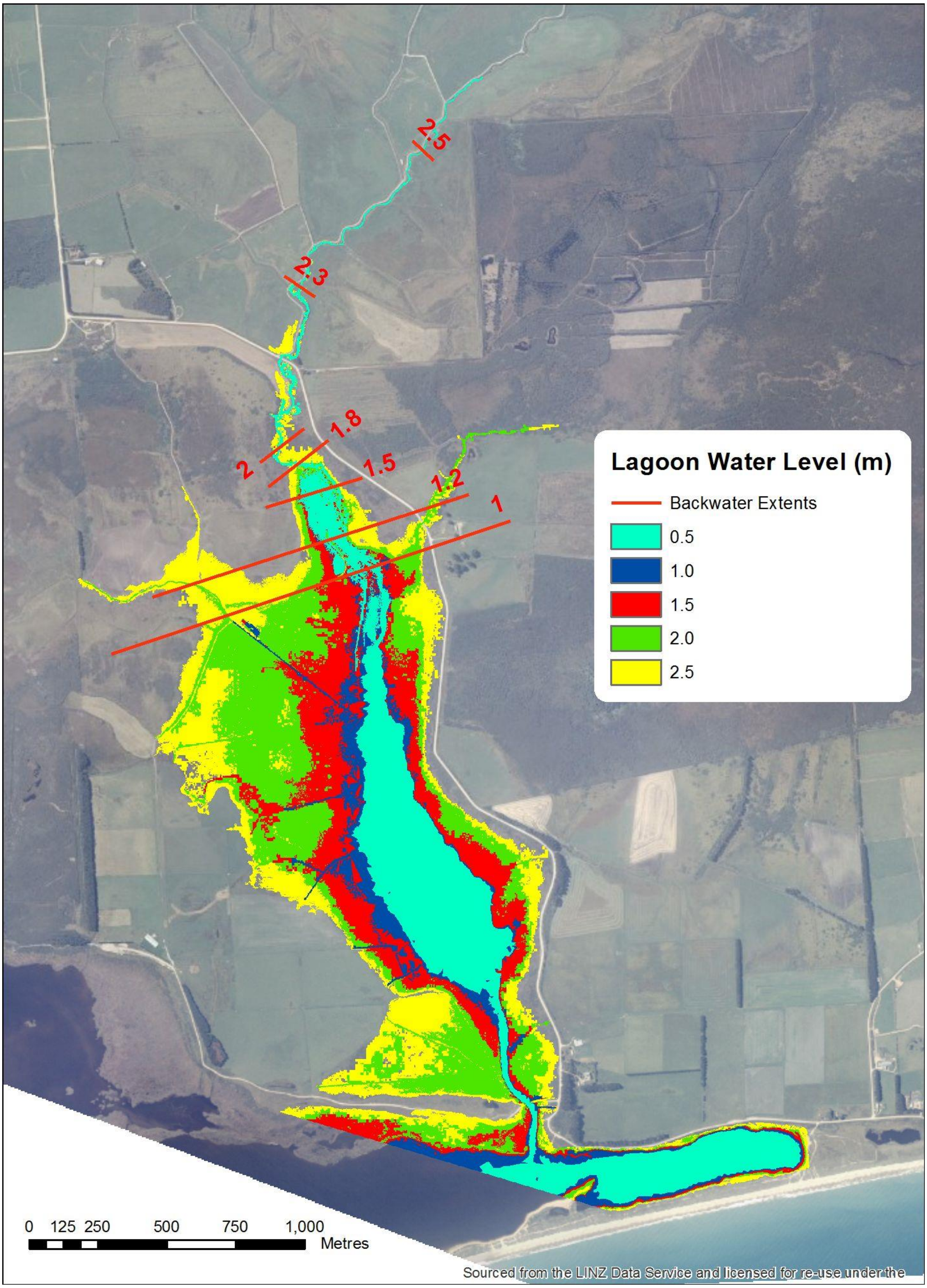

Figure D-7: Extent of Inundated land from Carran Creek and of the backwater effect from Waituna Lagoon for scenario "Q_{90}-Channel Vegetated". Inundated land is mapped for lagoon water levels of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. The red lines plot the maximum extent of the backwater effect at lagoon water levels as annotated on the line Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

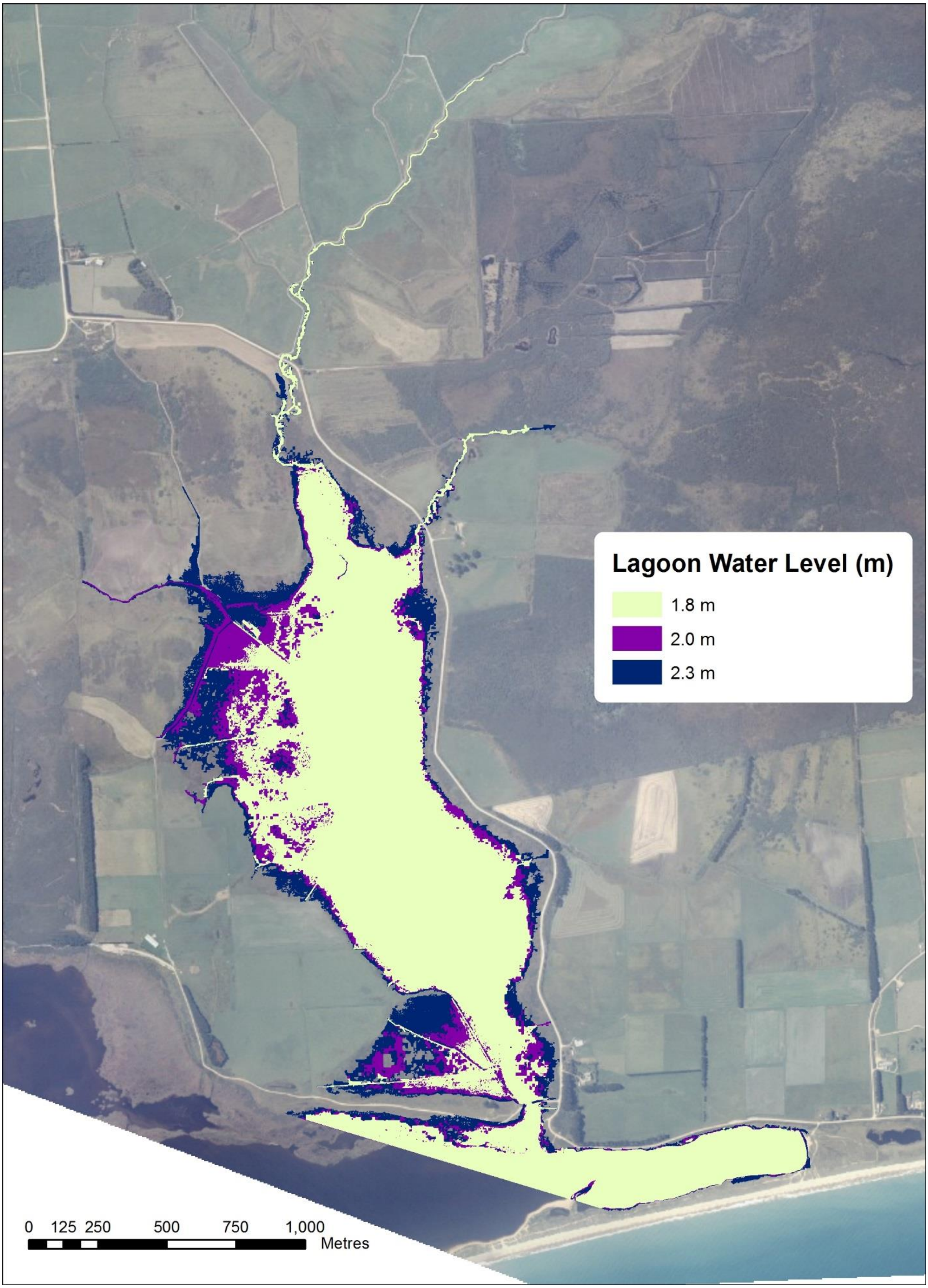

Figure D-8: Extent of Inundated land from Carran Creek for scenario “Q_{90}-Channel Vegetated” (specific lagoon levels of interest). Inundated land is mapped for lagoon water levels of 1.8 m, 2.0 m and 2.3 m. Scenario “Q_{90}-Channel Vegetated” models the 90 percentile high flow with a vegetated main channel.

Appendix E Waituna Creek potentially drainage affected land (1m threshold)

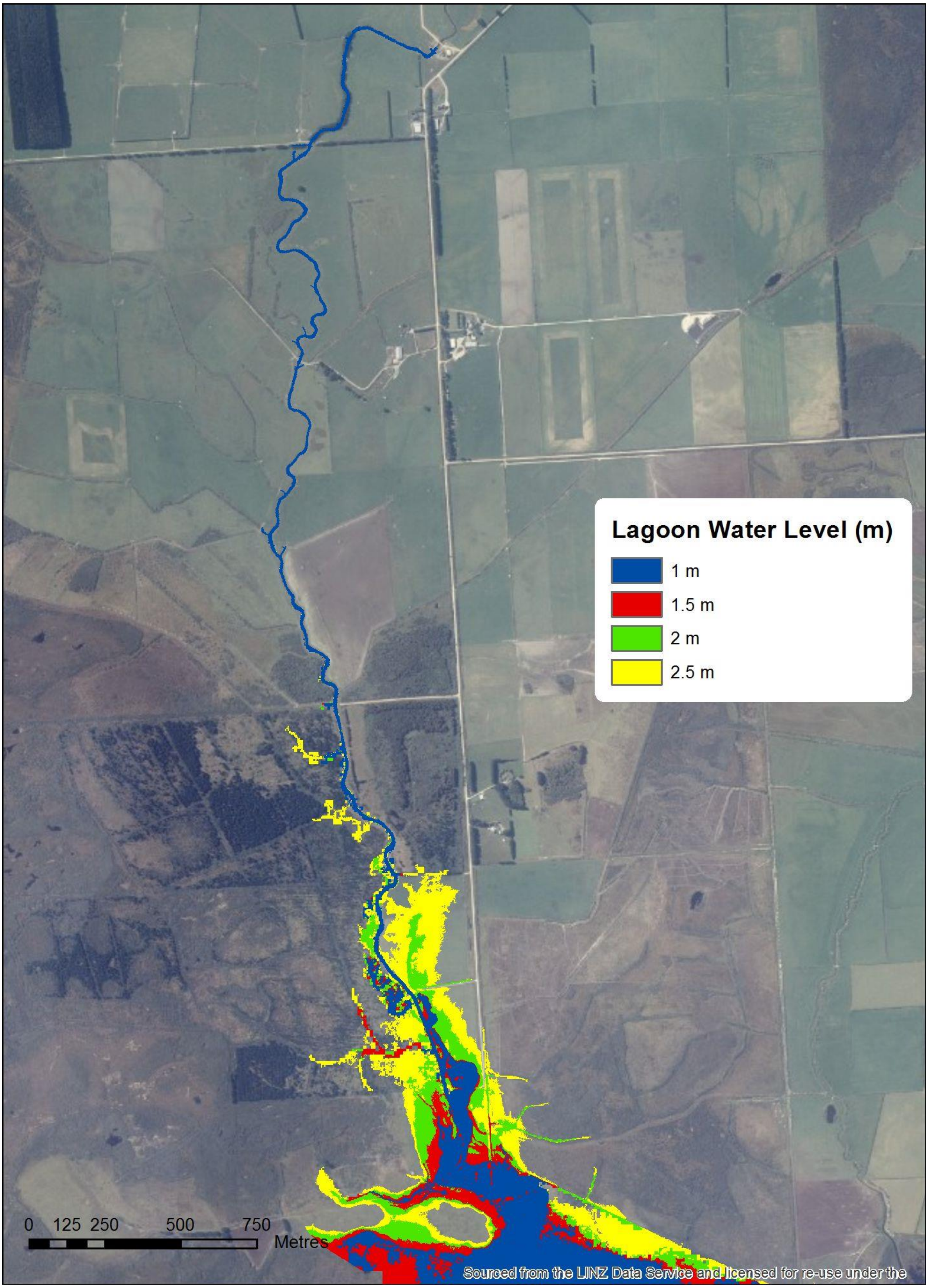

Figure E-1: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

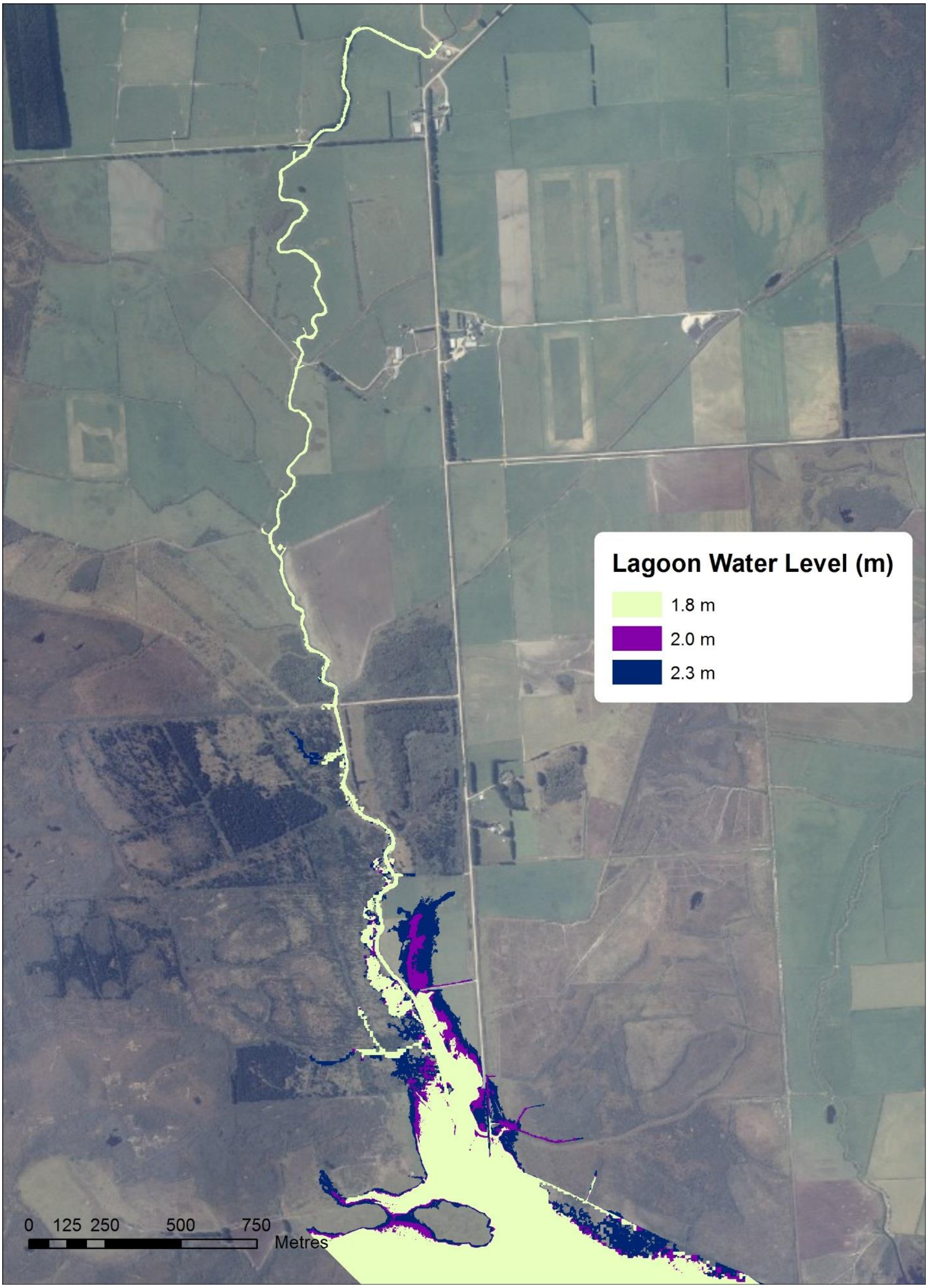

Figure E-2: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

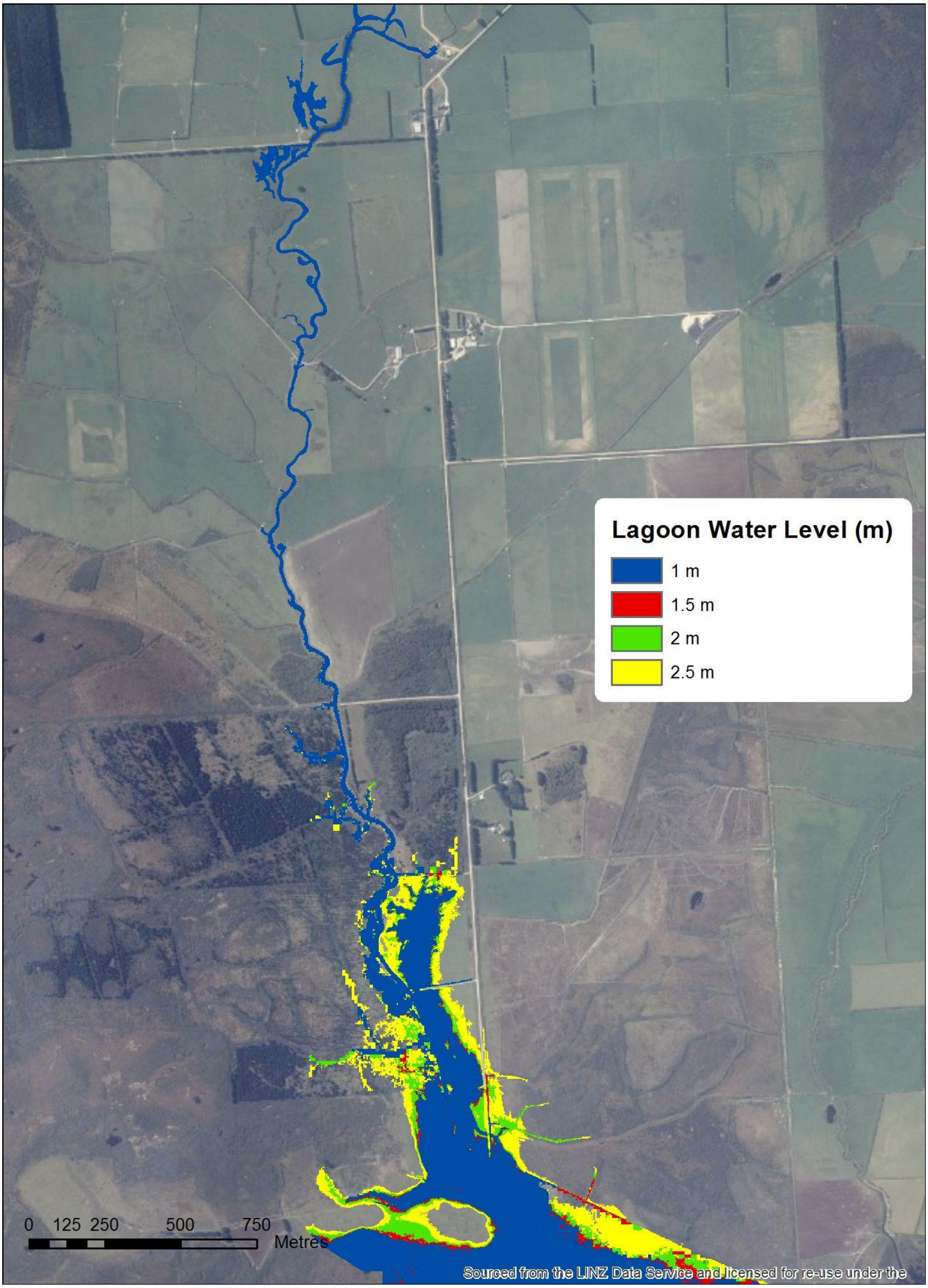

Figure E-3: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

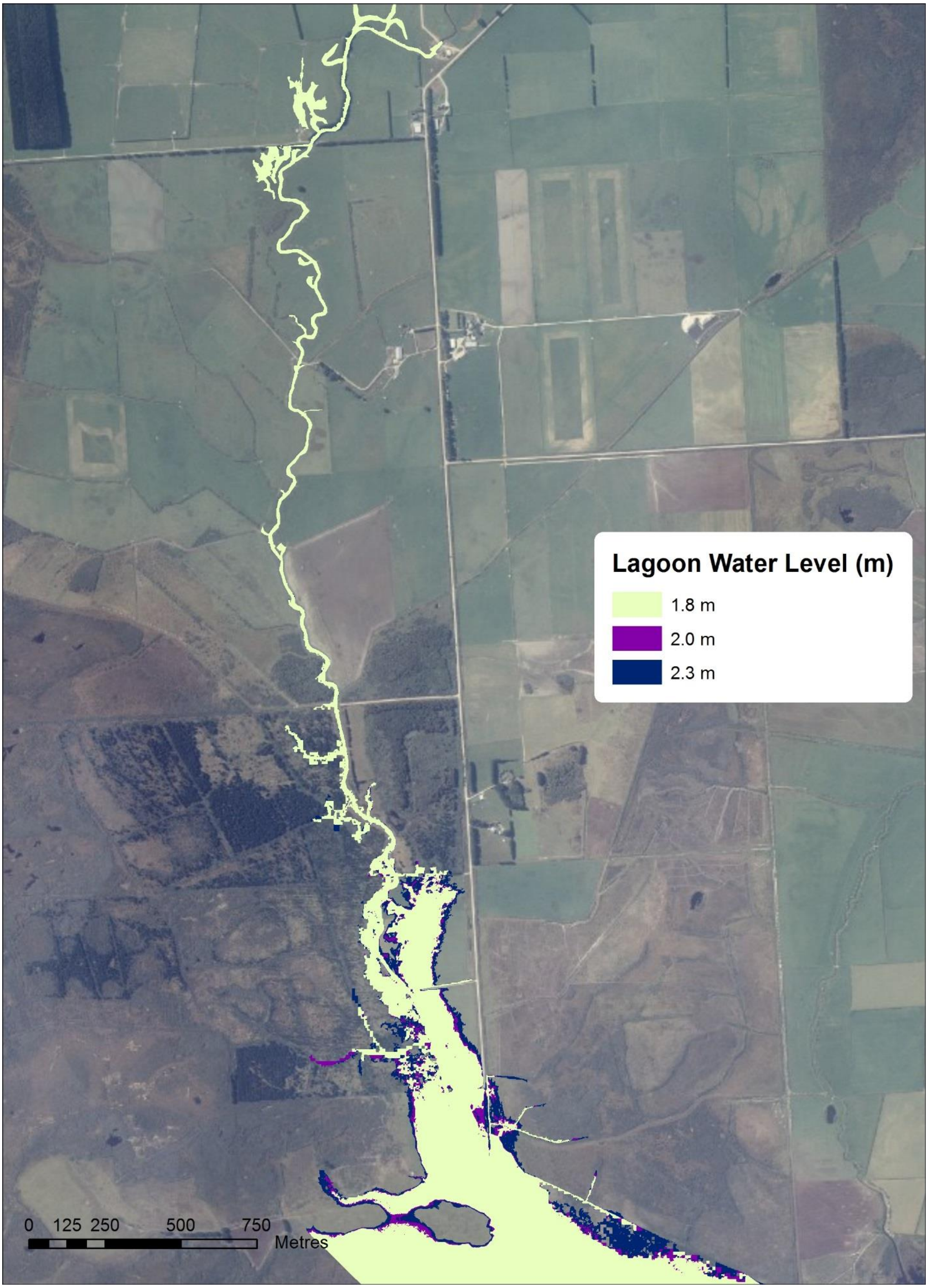

Figure E-4: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

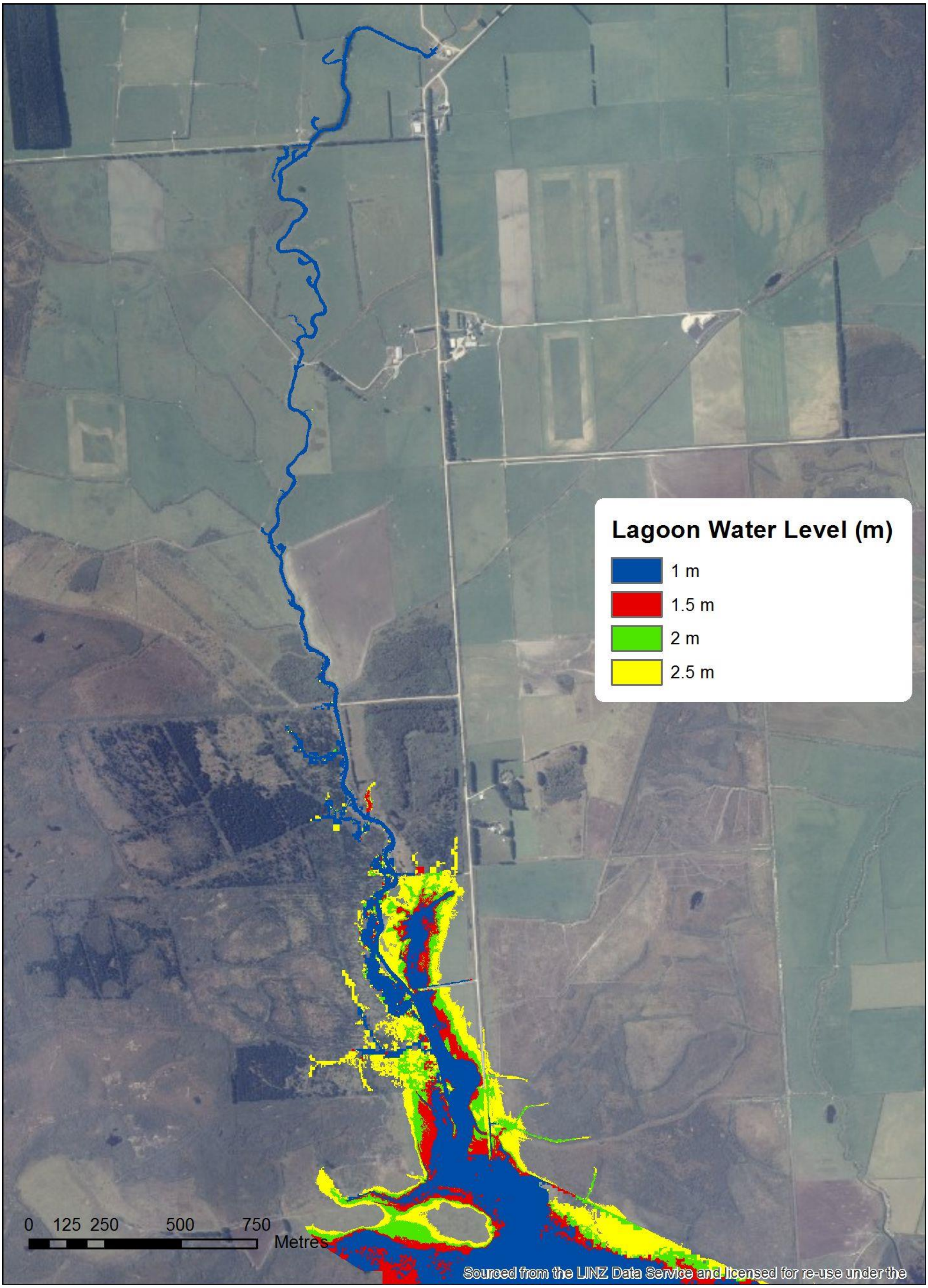

Figure E-5: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

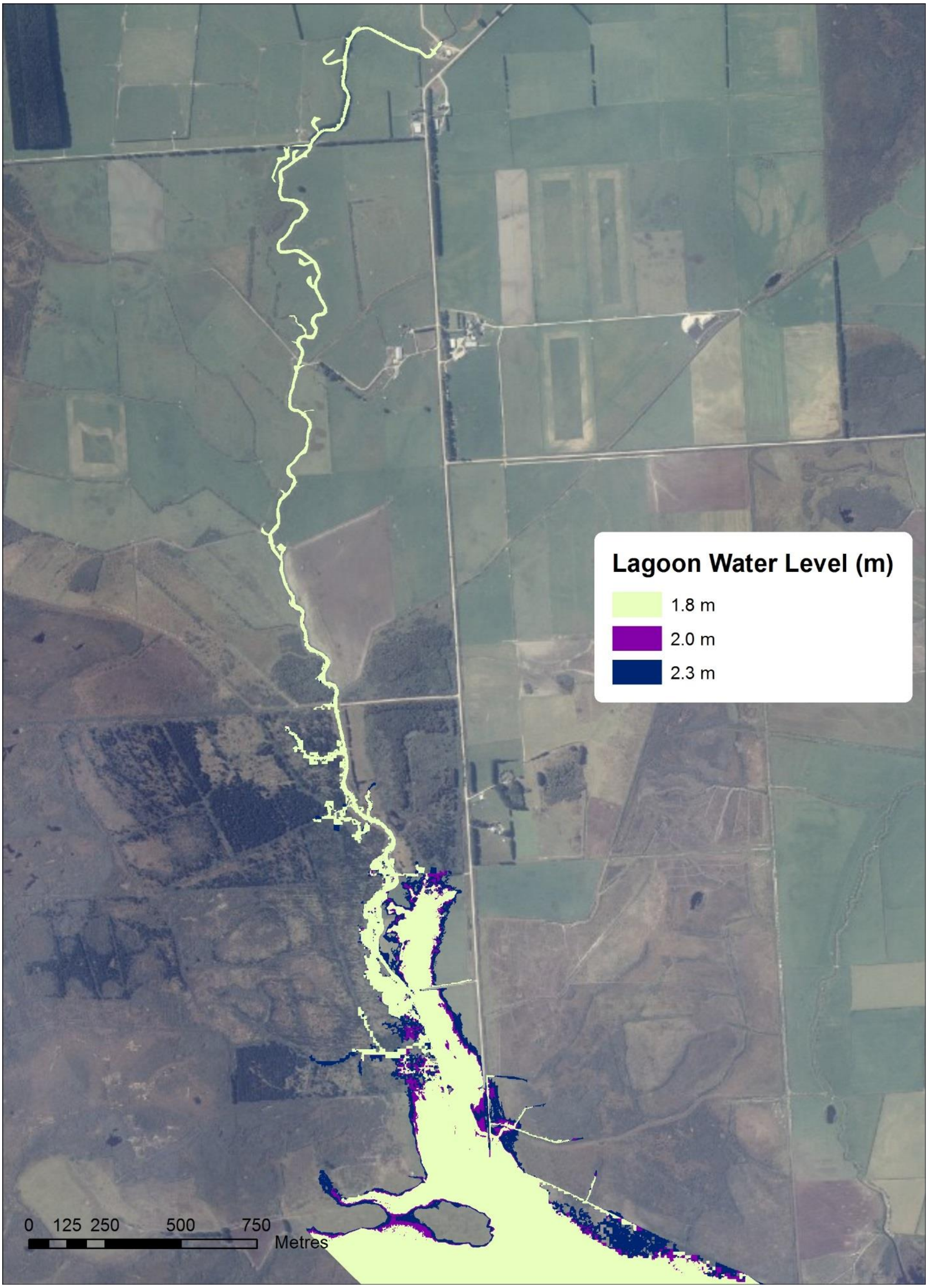

Figure E-6: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

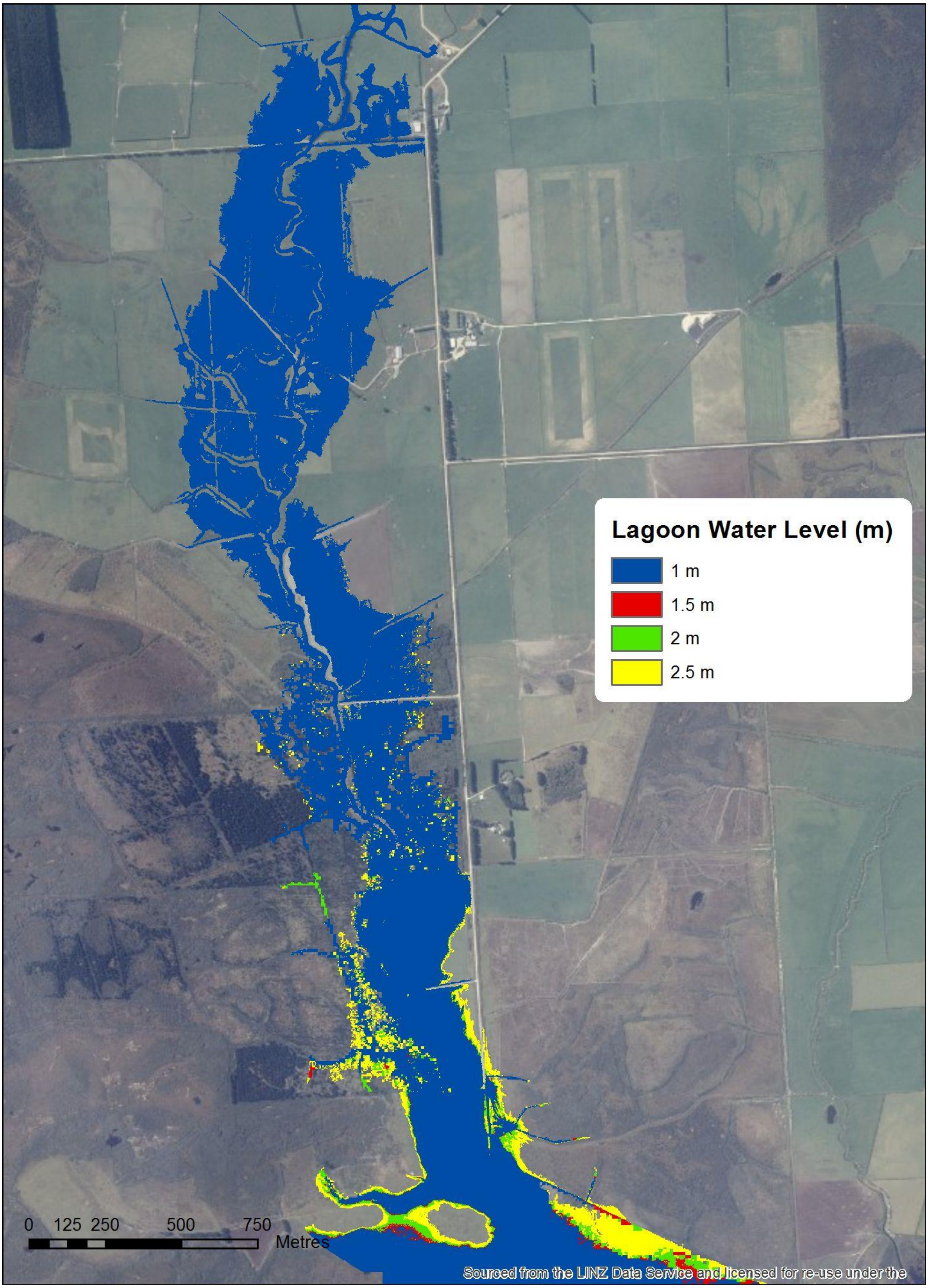

Figure E-7: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

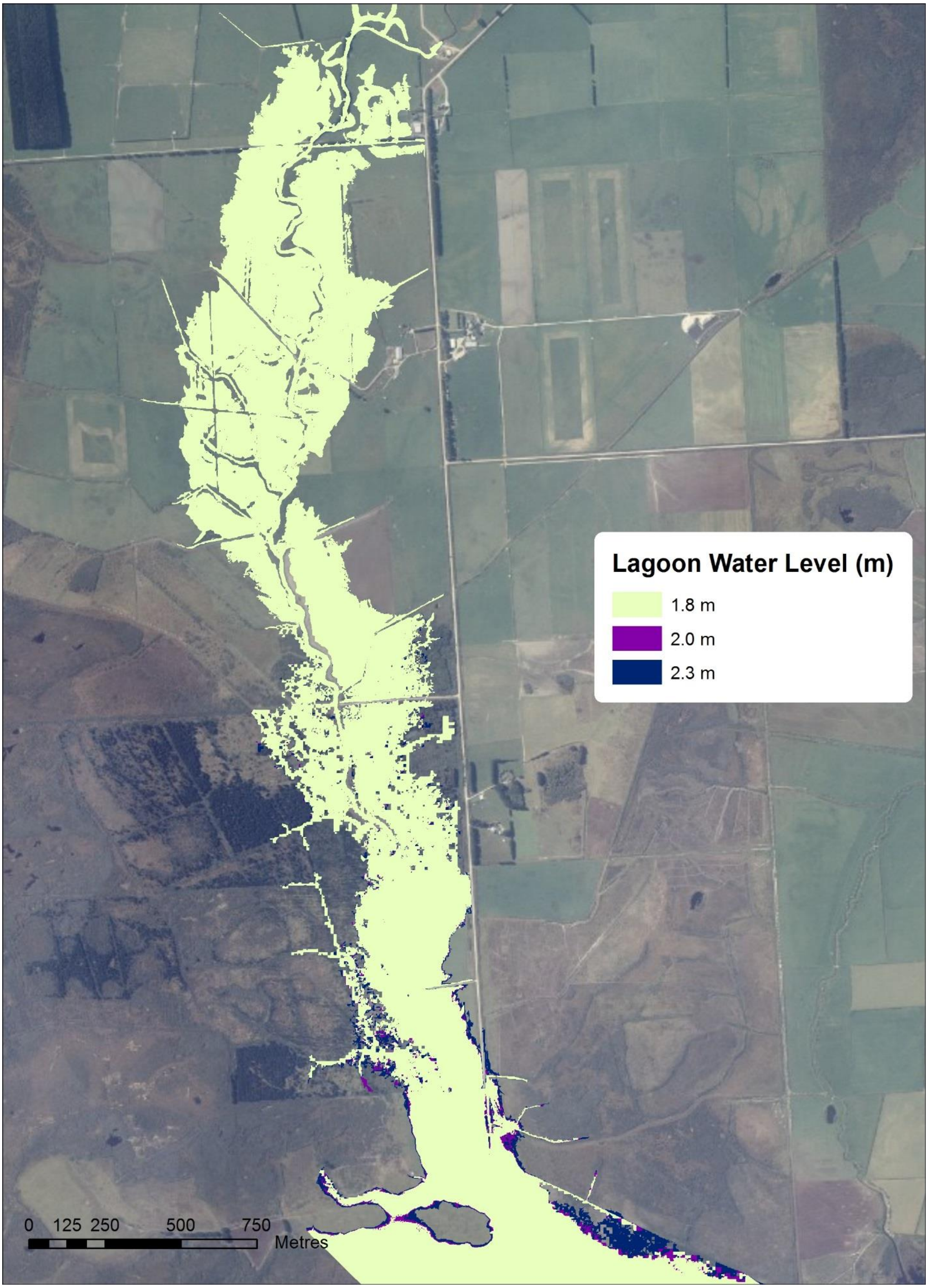

Figure E-8: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile flow with a vegetated main channel.

Appendix F Moffat Creek potentially drainage affected land (1m threshold)

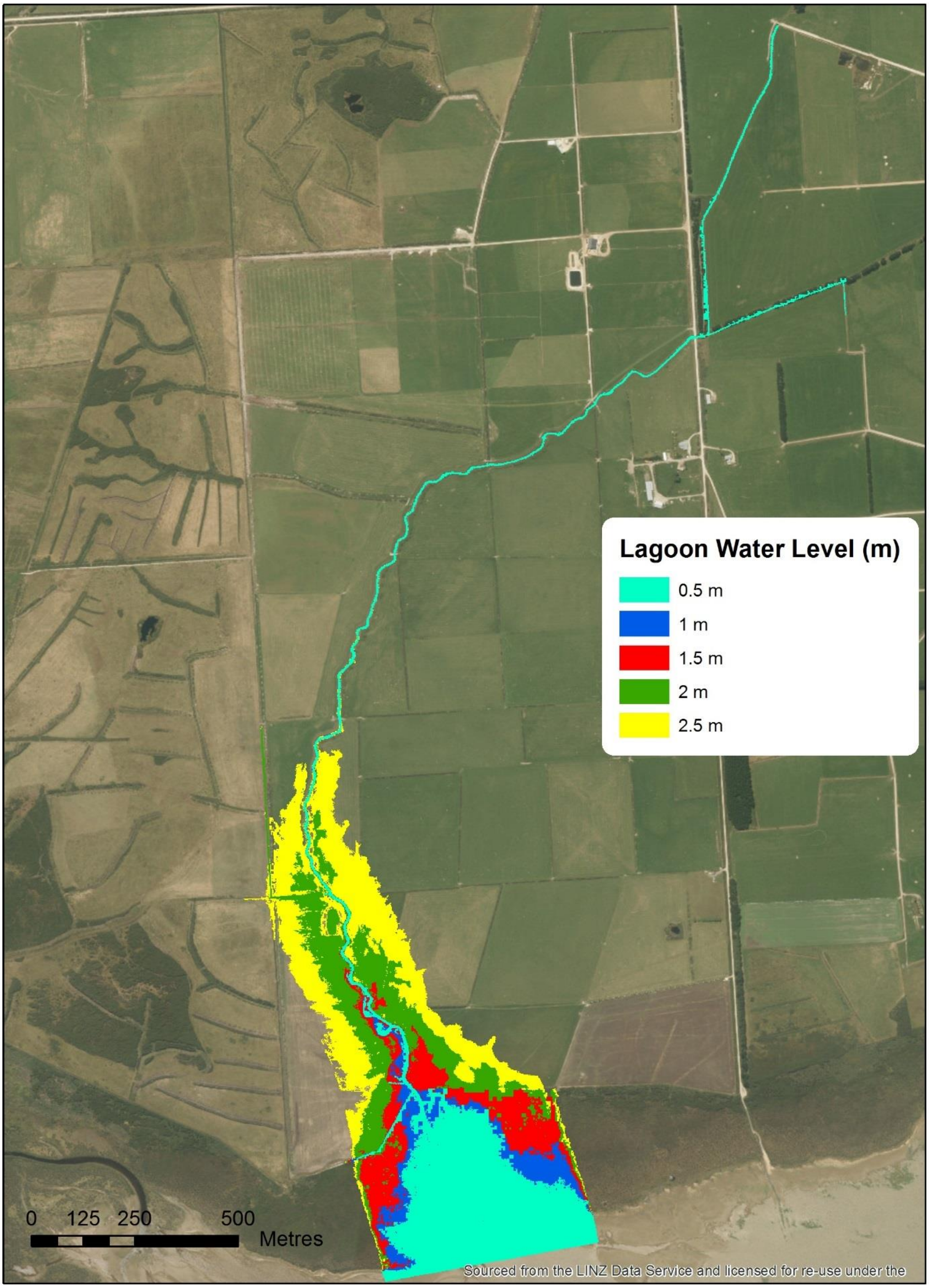

Figure F-1: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

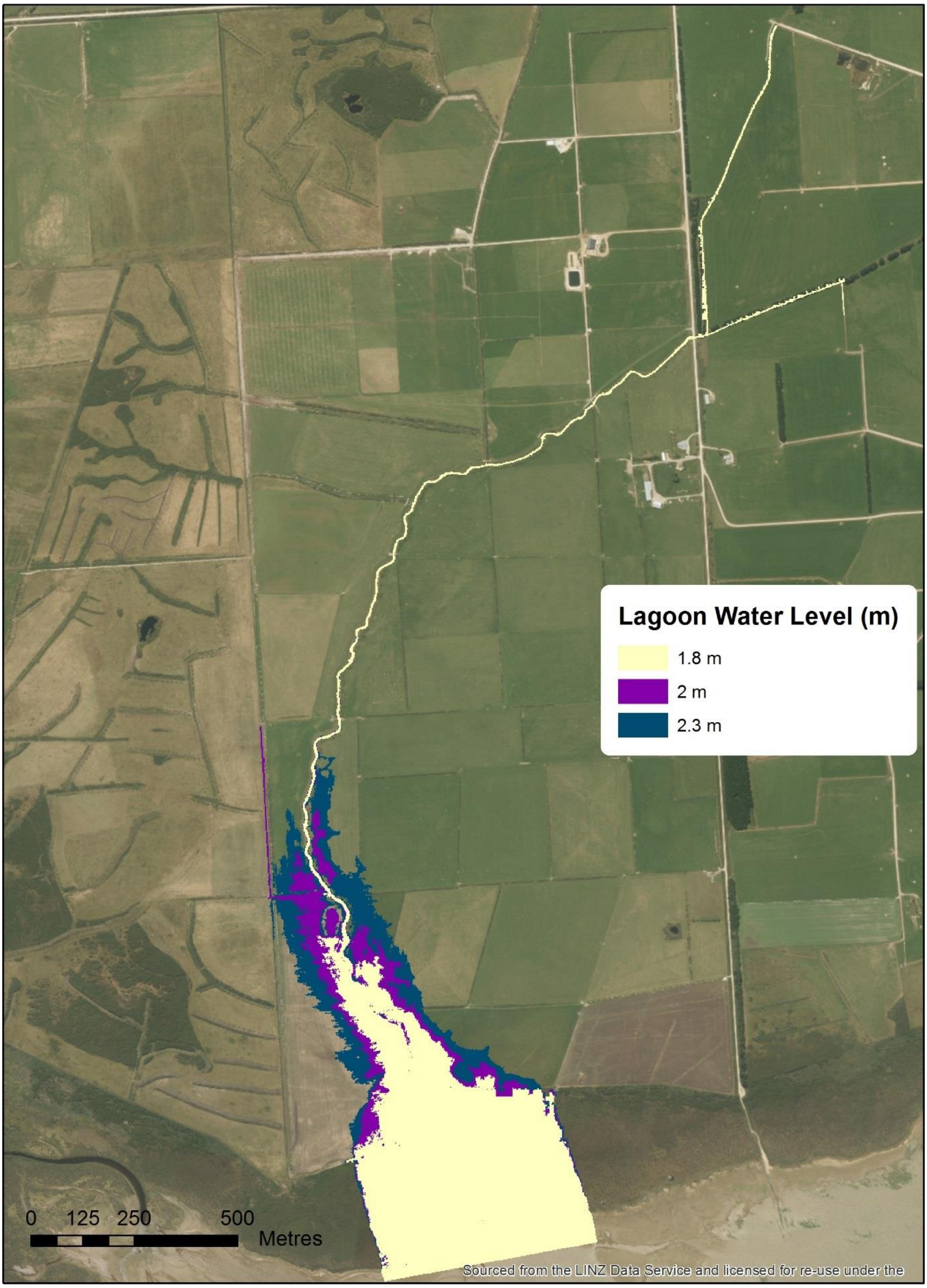

Figure F-2: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

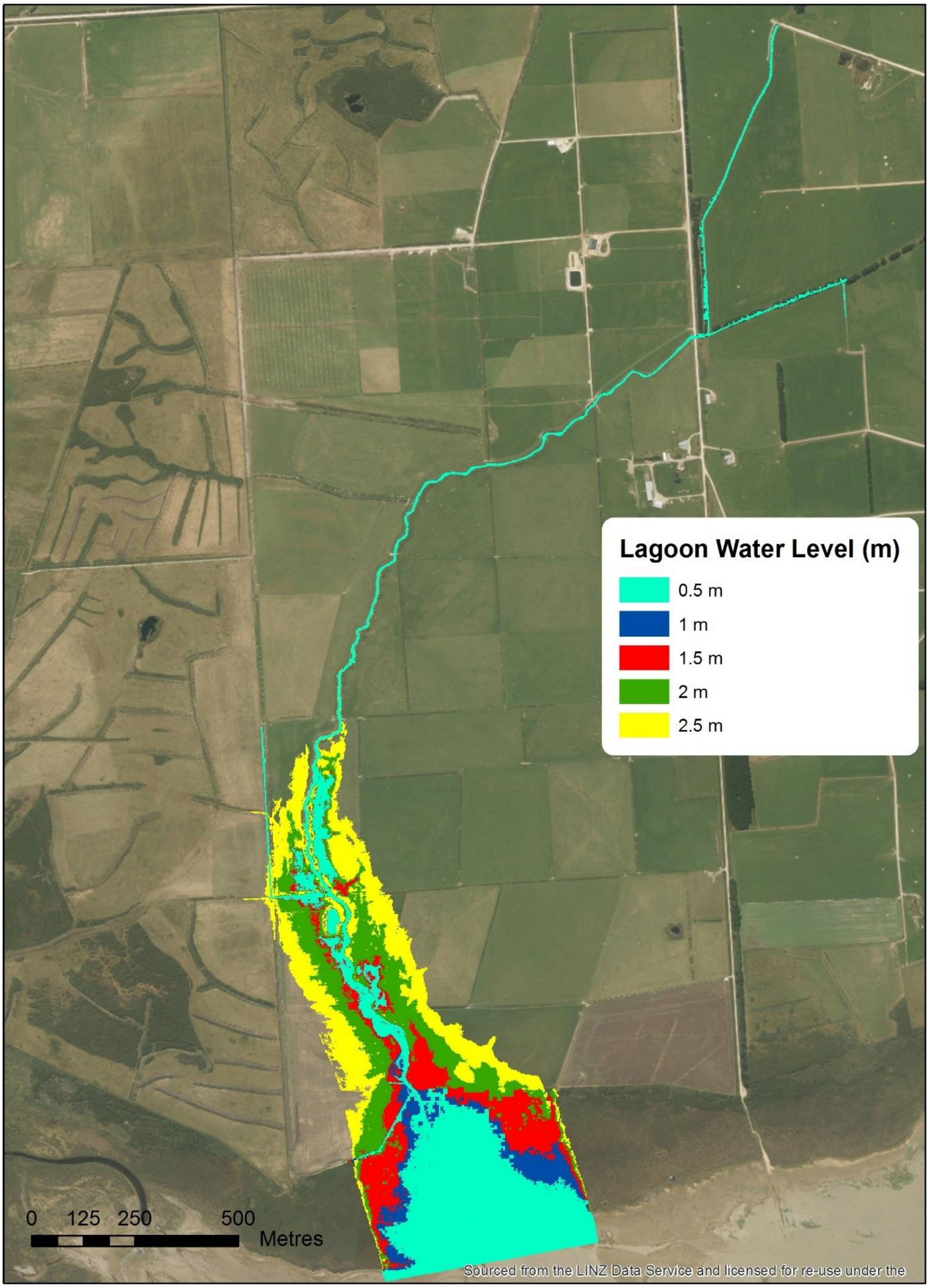

Figure F-3: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

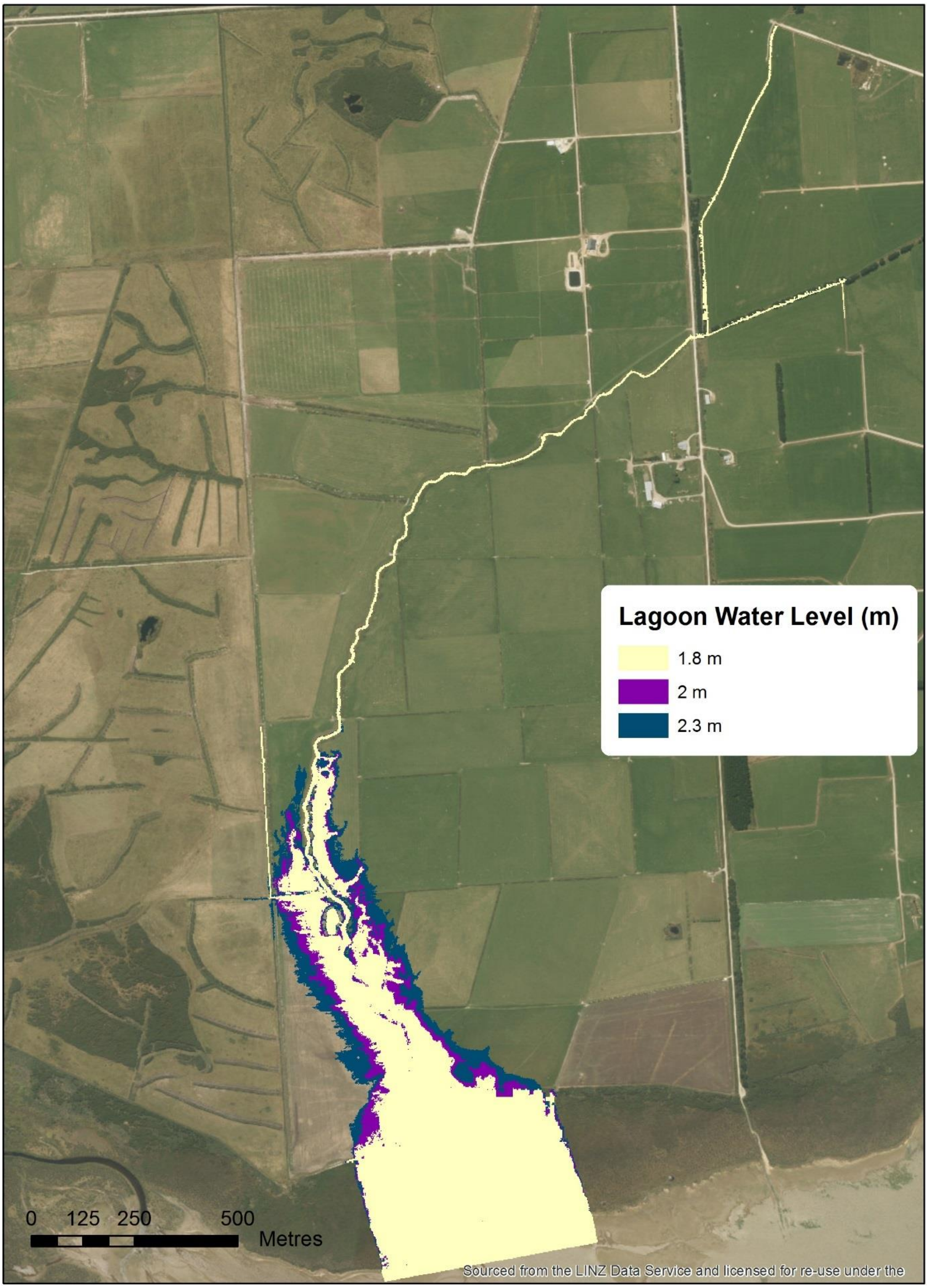

Figure F-4: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

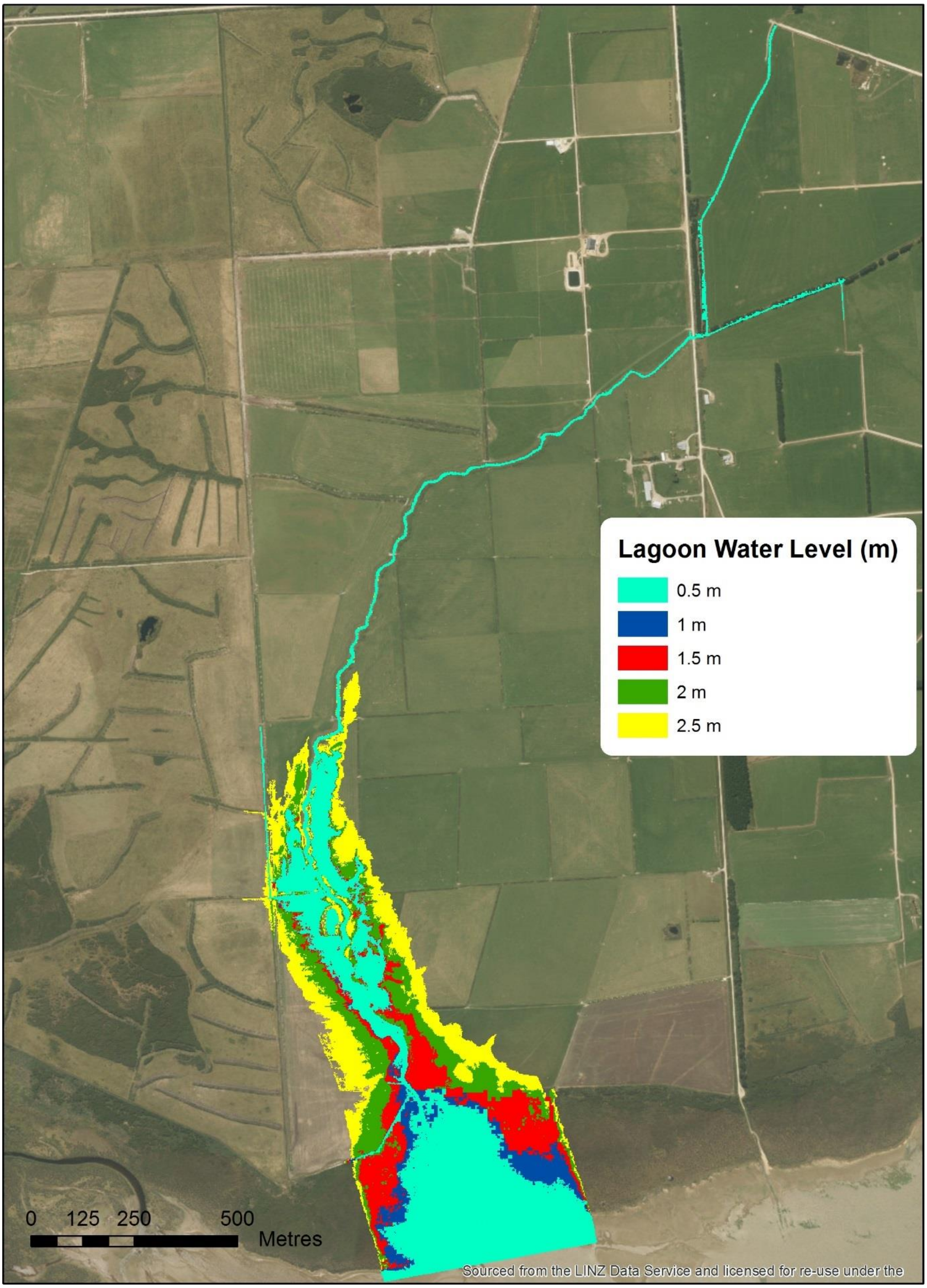

Figure F-5: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

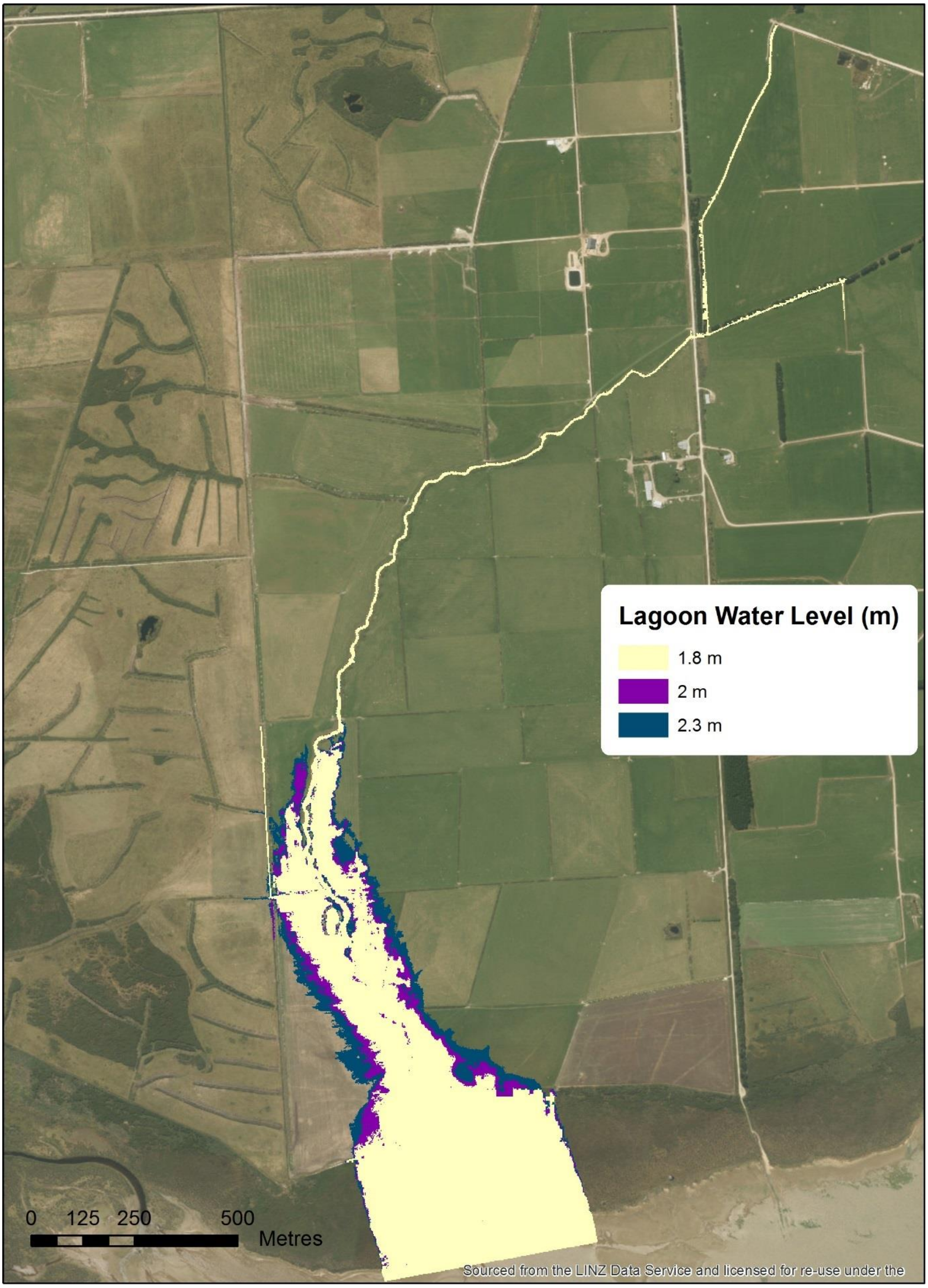

Figure F-6: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

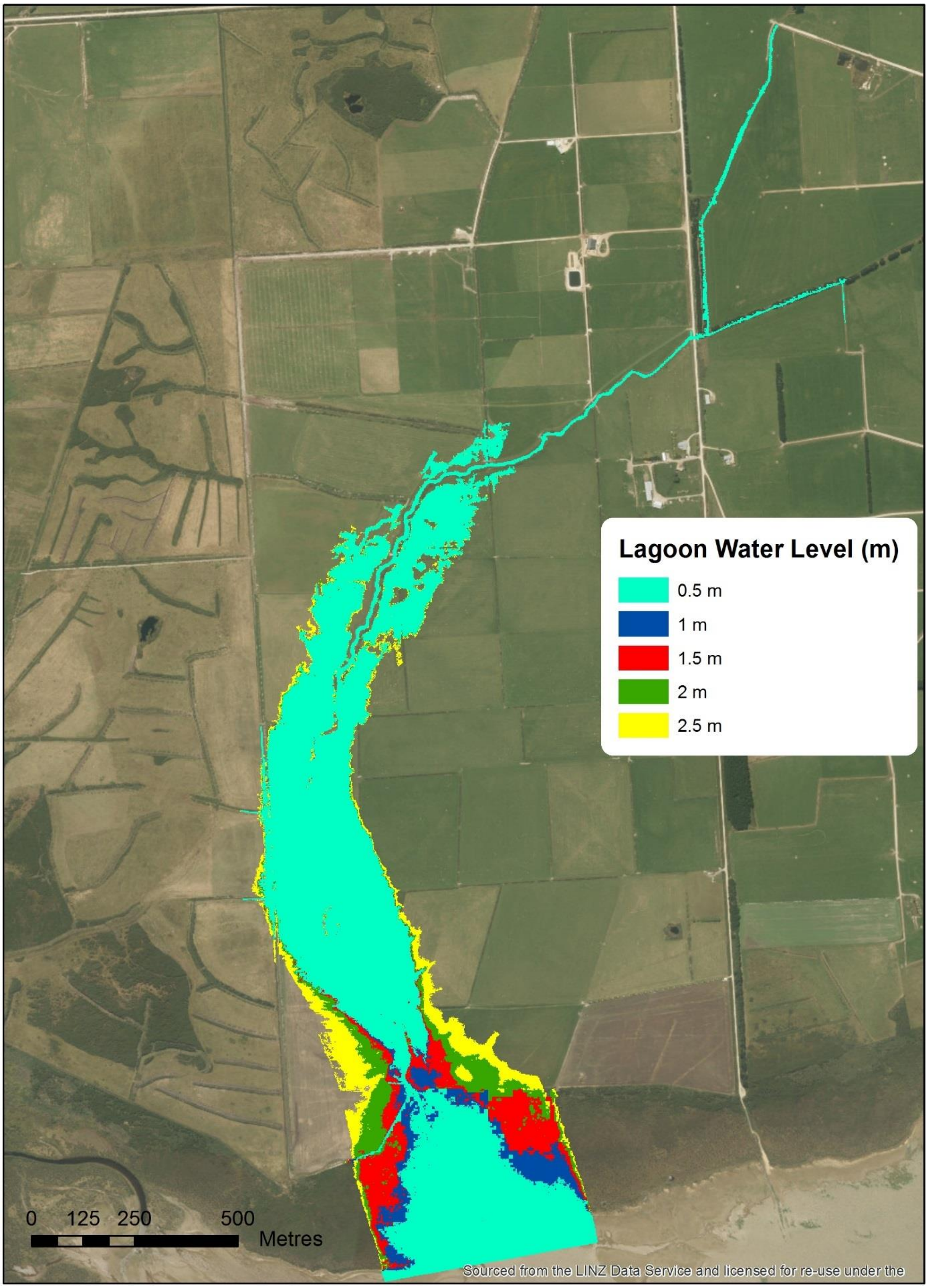

Figure F-7: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

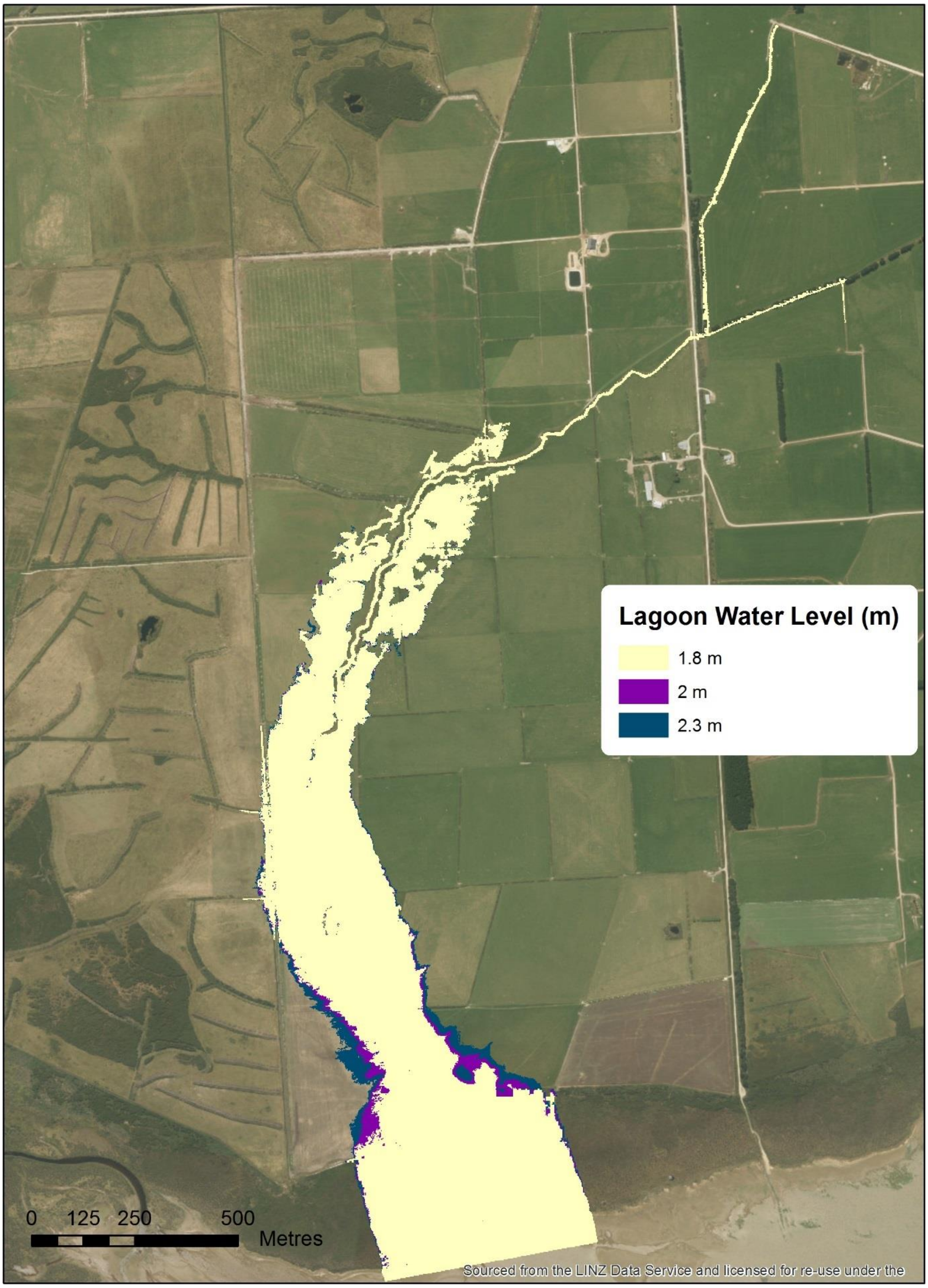

Figure F-8: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile flow with a vegetated main channel.

Appendix G Carran Creek potentially drainage affected land (1m threshold)

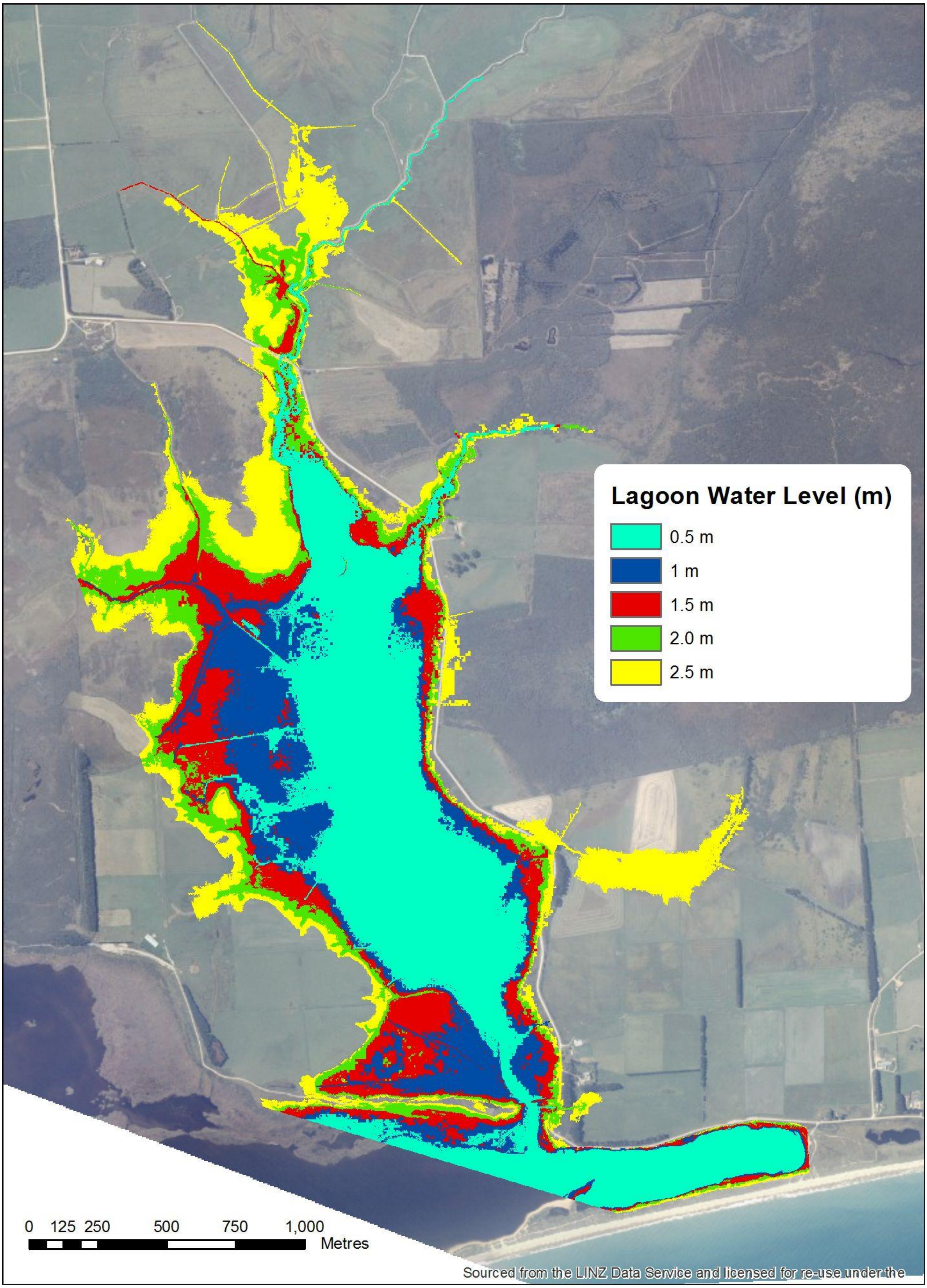

Figure G-1: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

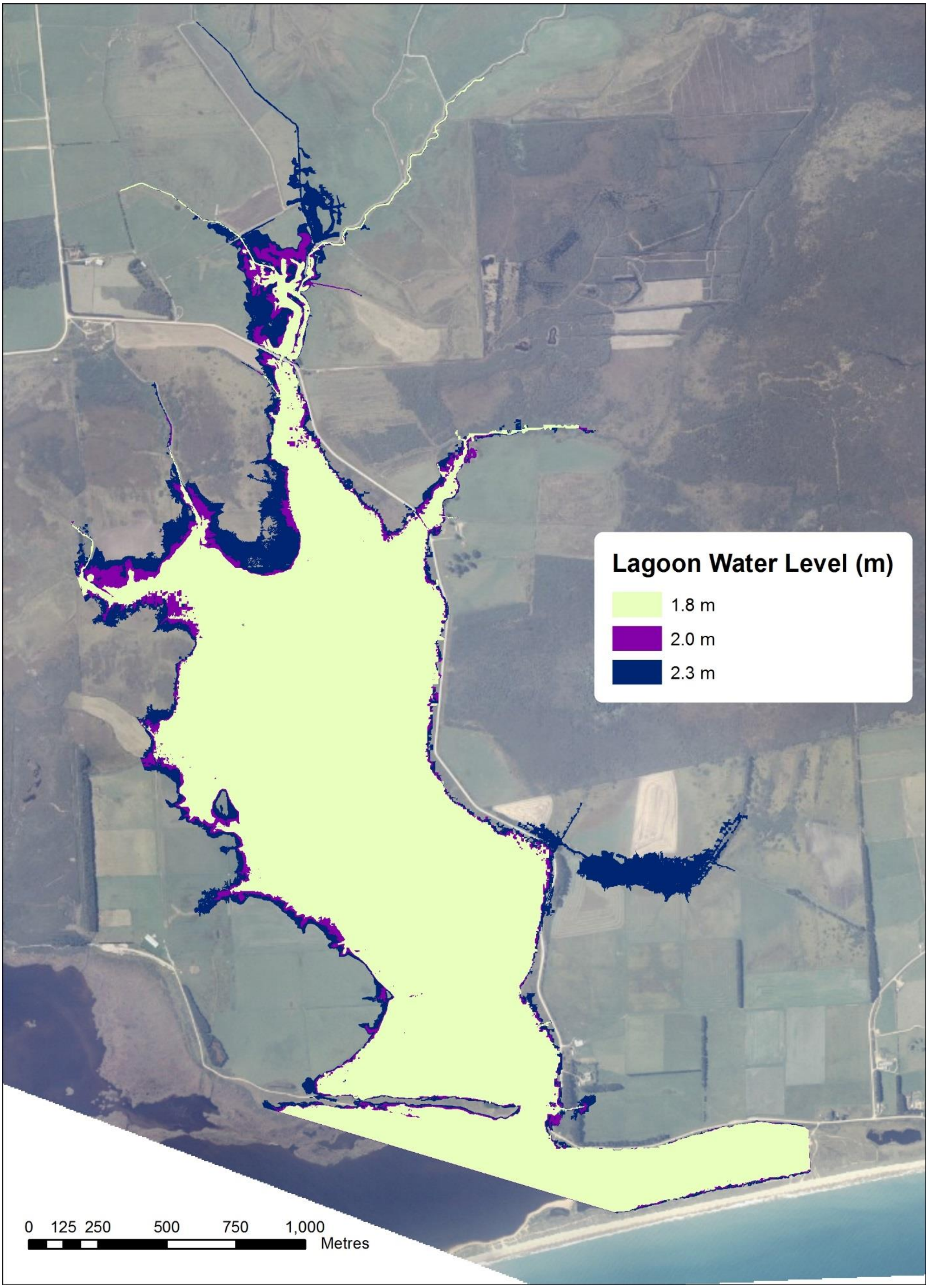

Figure G-2: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

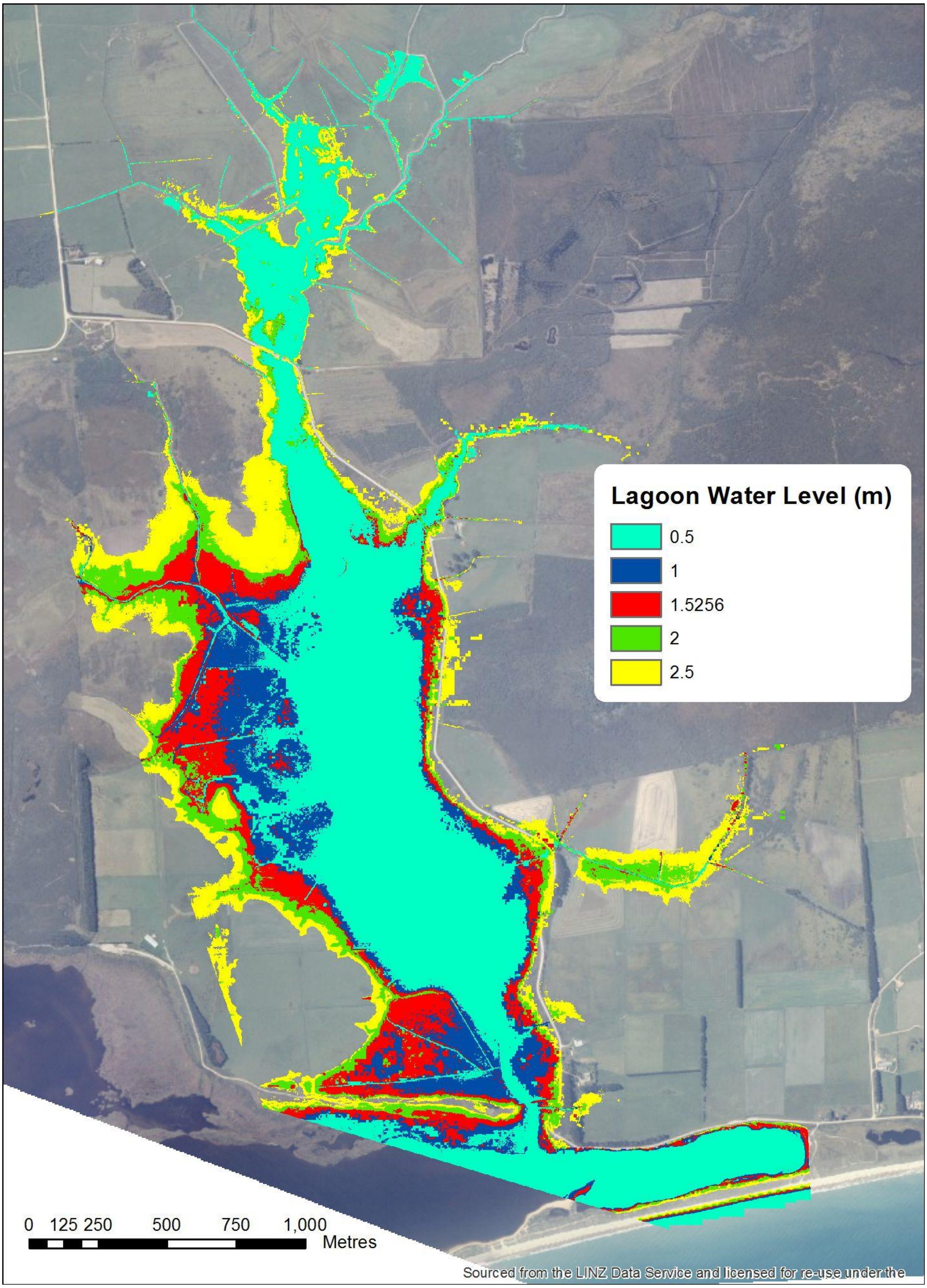

Figure G-3: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

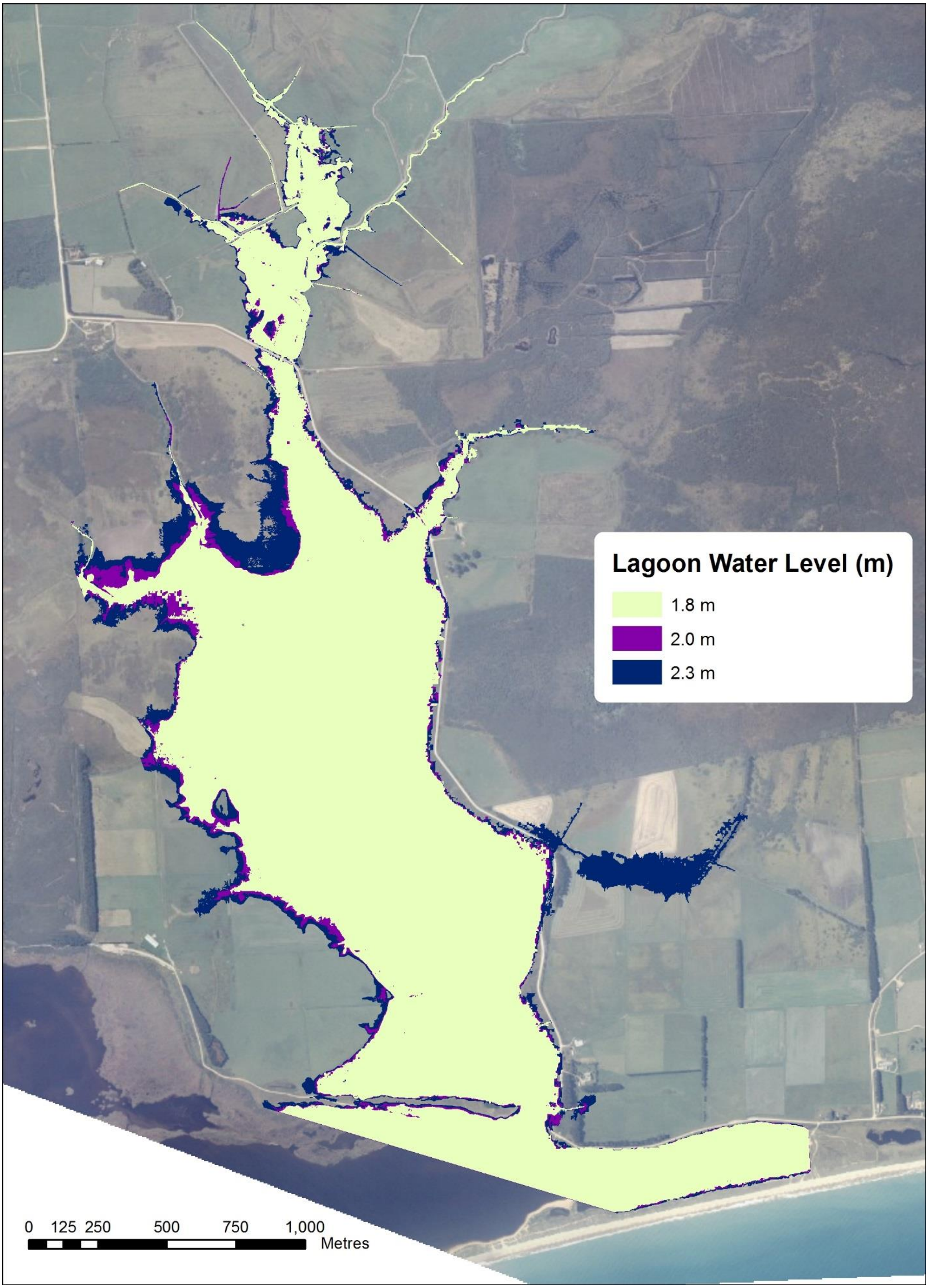

Figure G-4: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q$_{90}$-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q$_{90}$-Channel Cleared" models 90 percentile high flow with a recently cleared main channel.

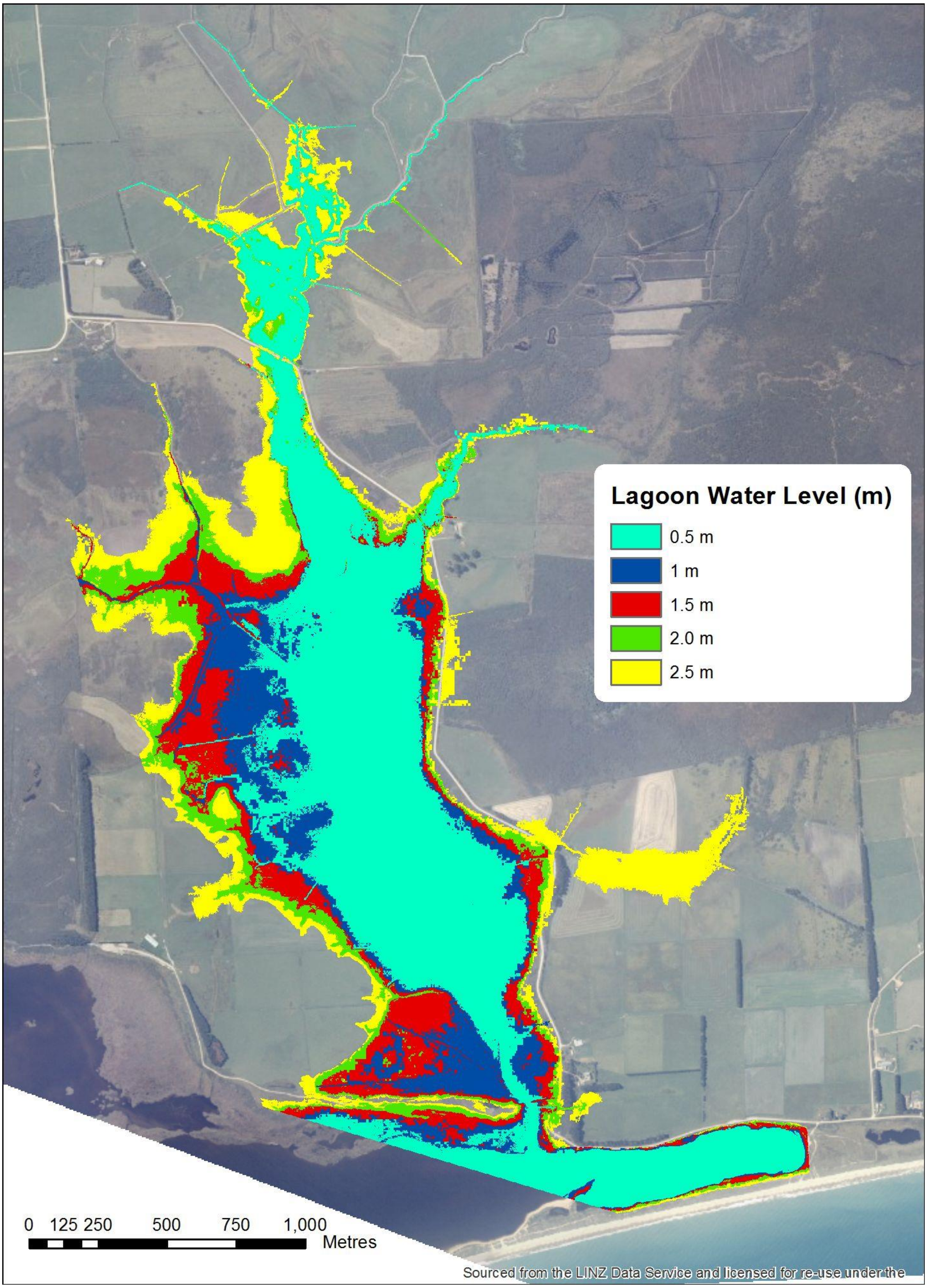

Figure G-5: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

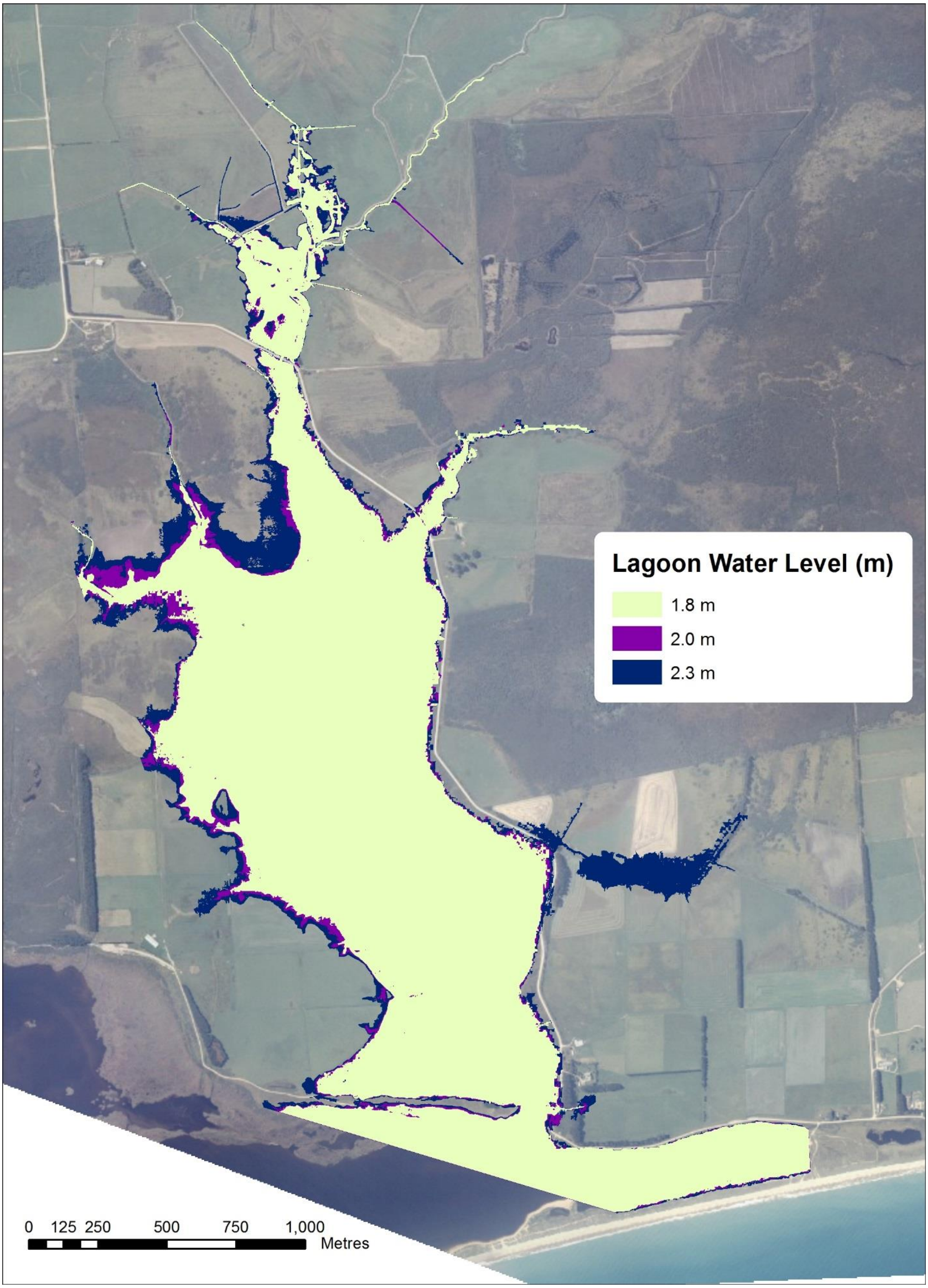

Figure G-6: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

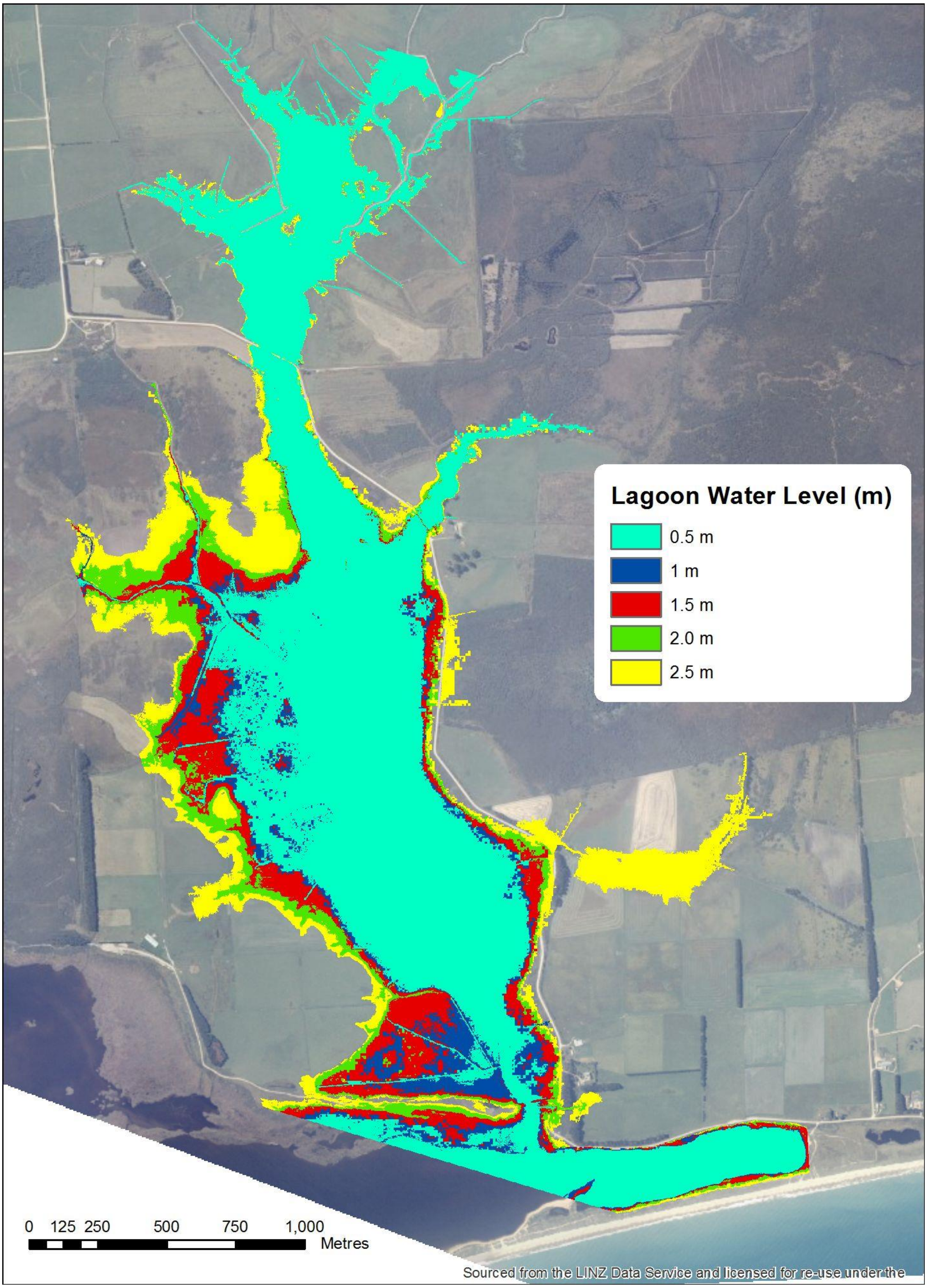

Figure G-7: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

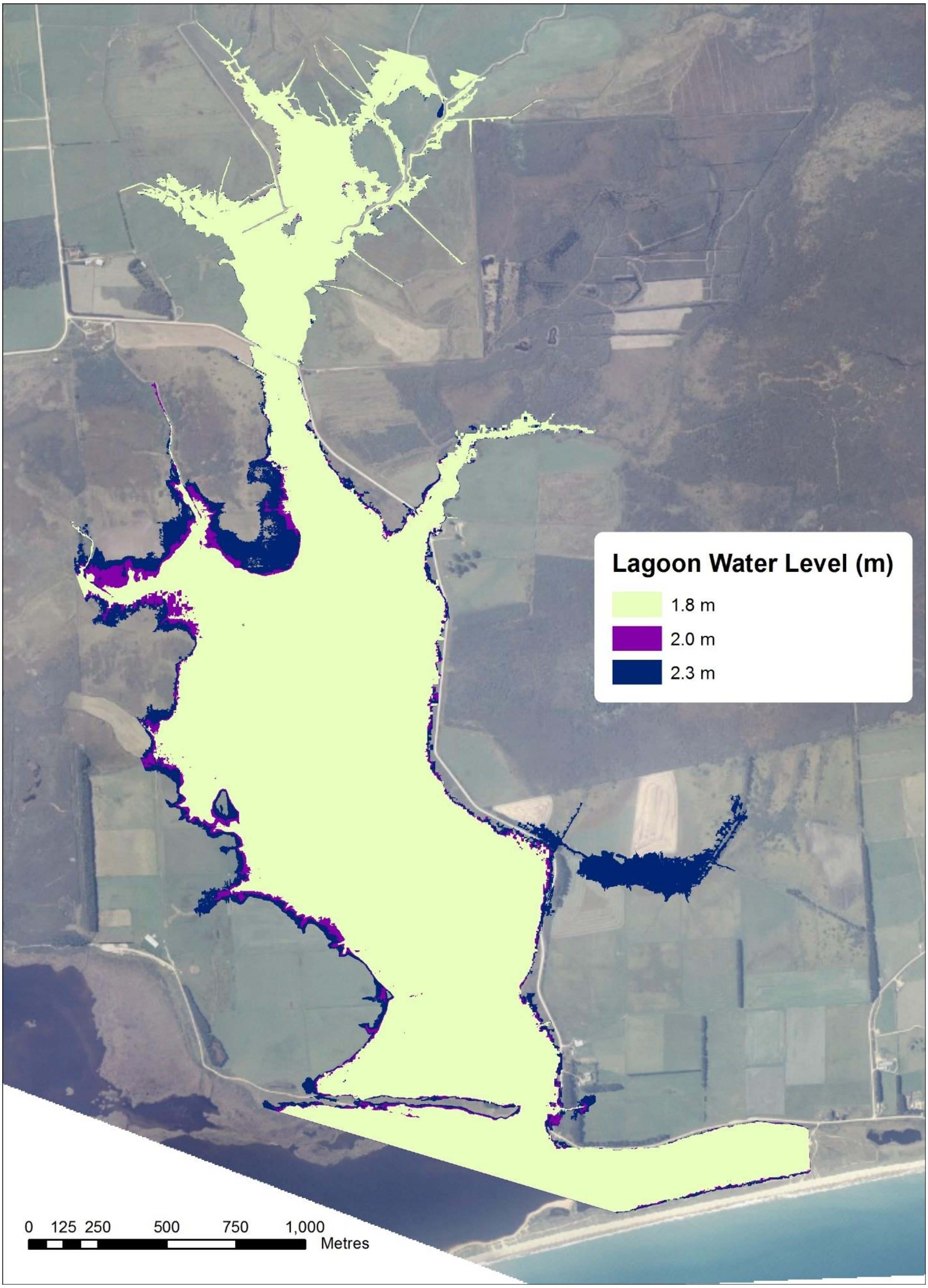

Figure G-8: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 1.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

Appendix H Waituna Creek potentially drainage affected land (2m threshold)

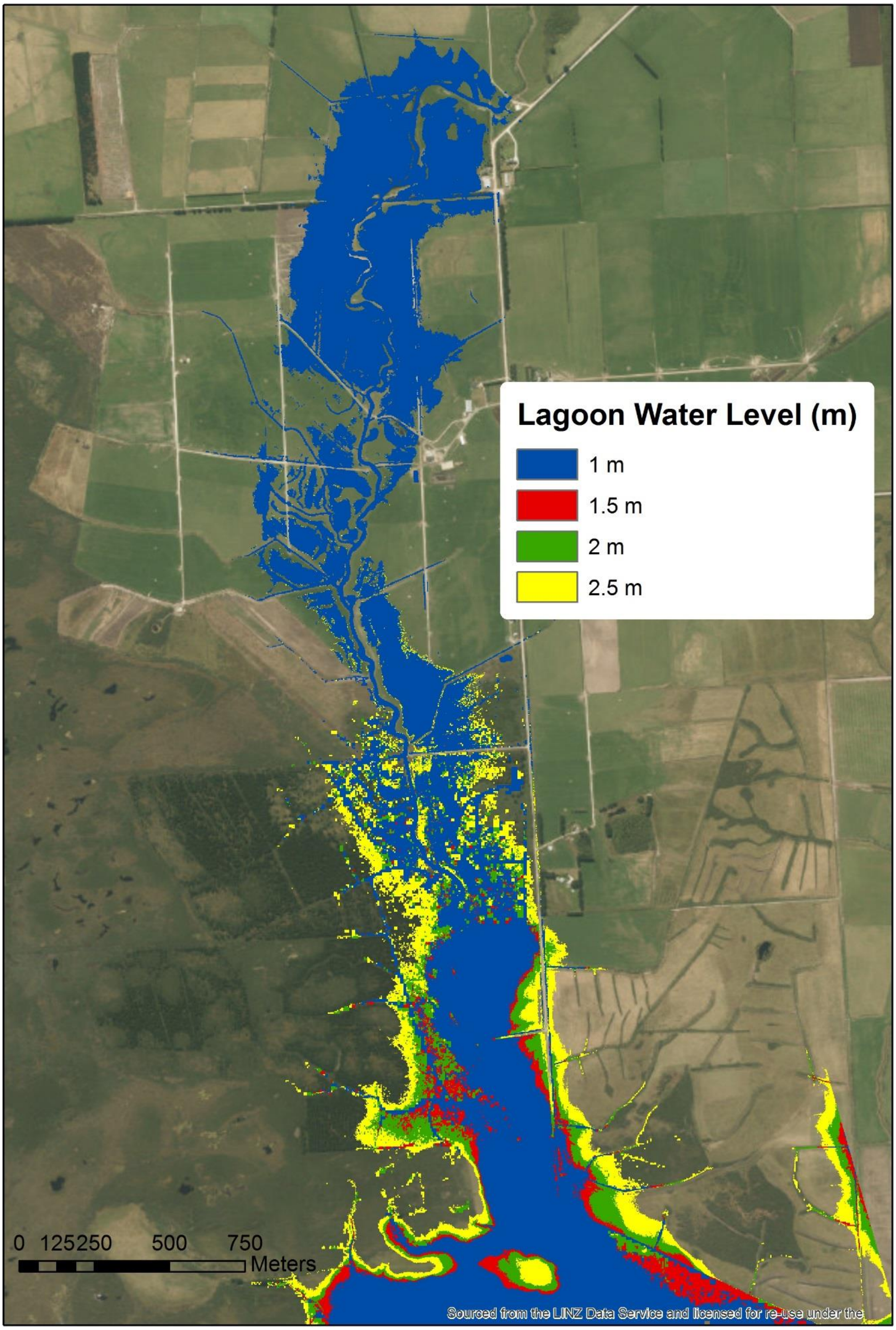

Figure H-1: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

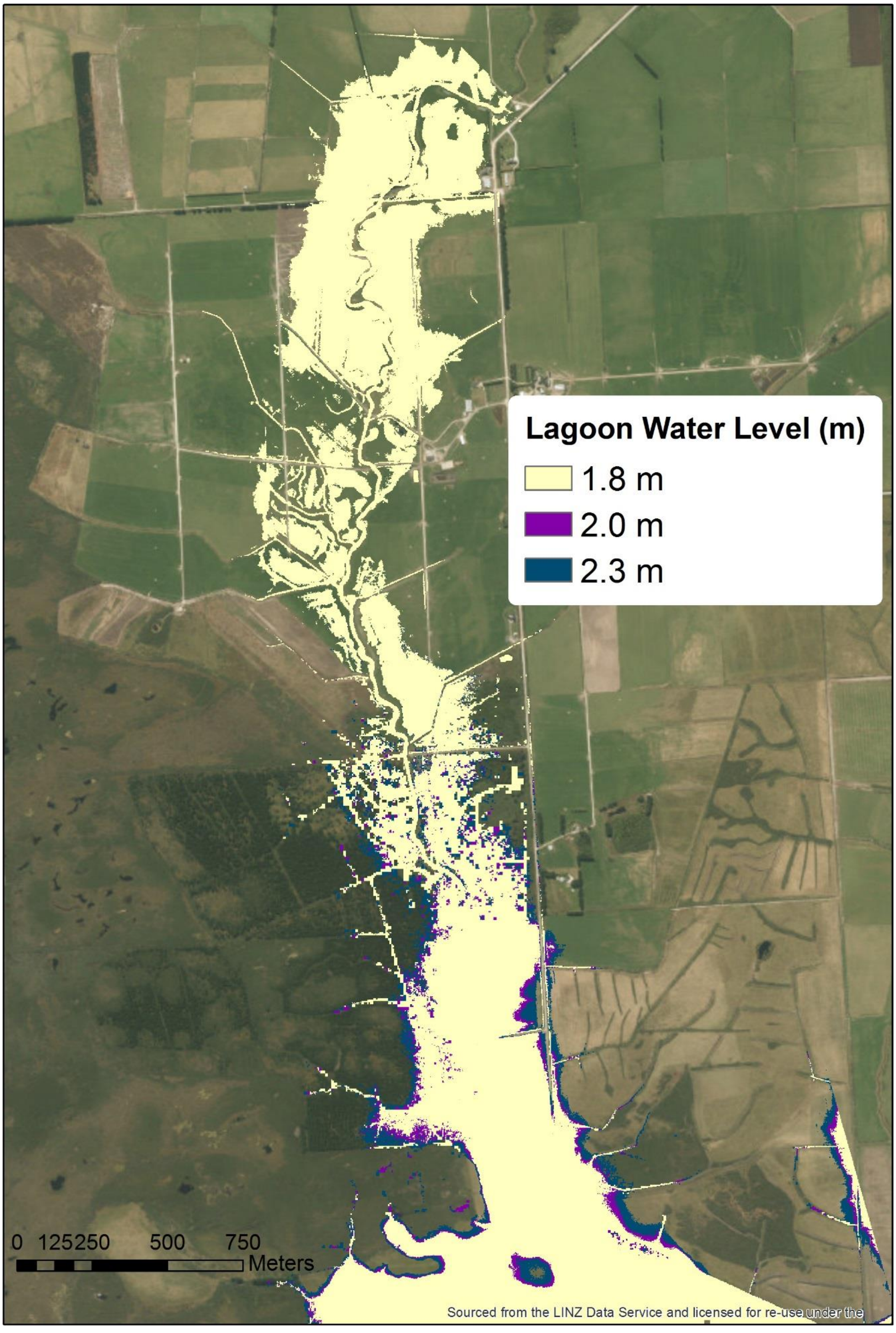

Figure H-2: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

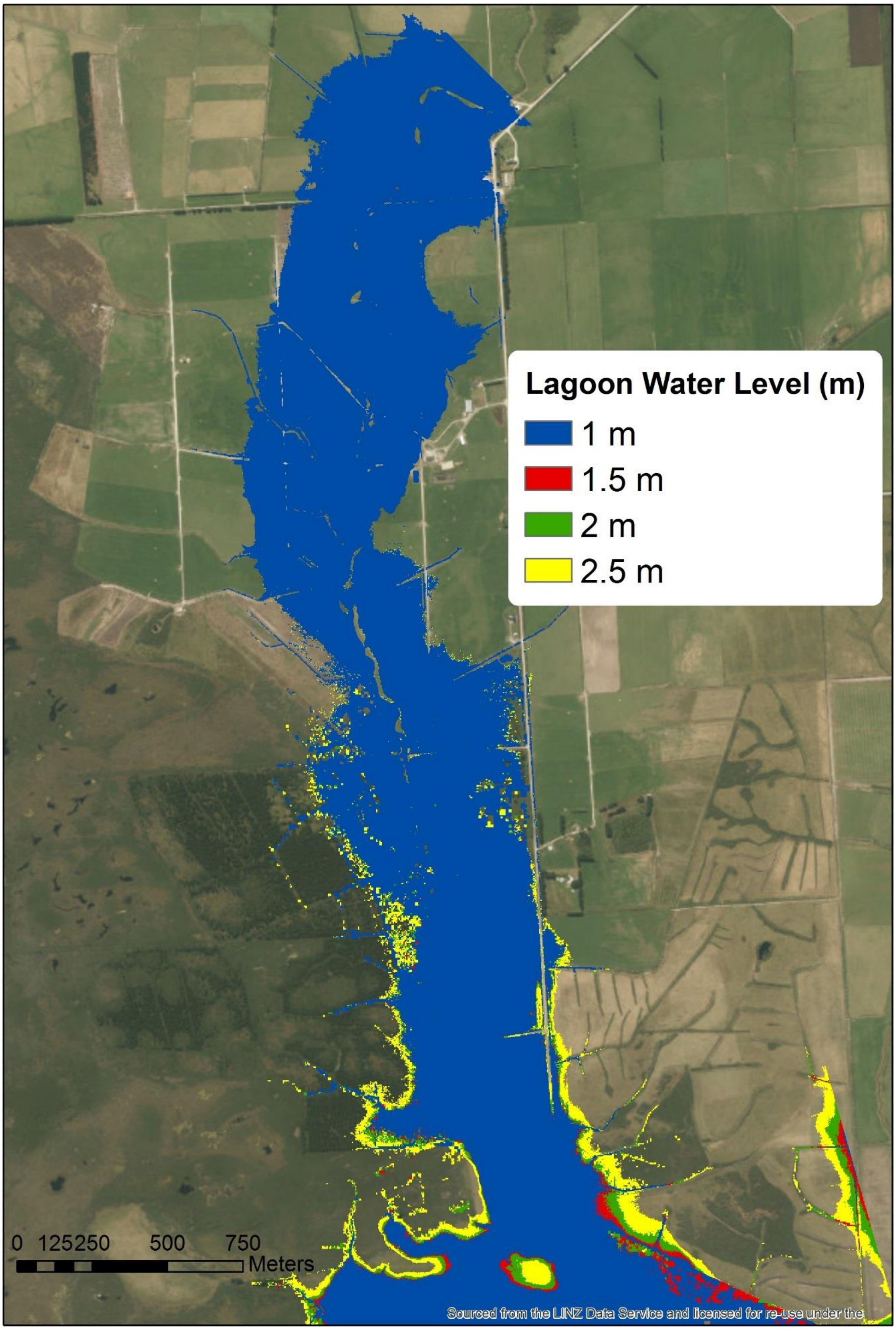

Figure H-3: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

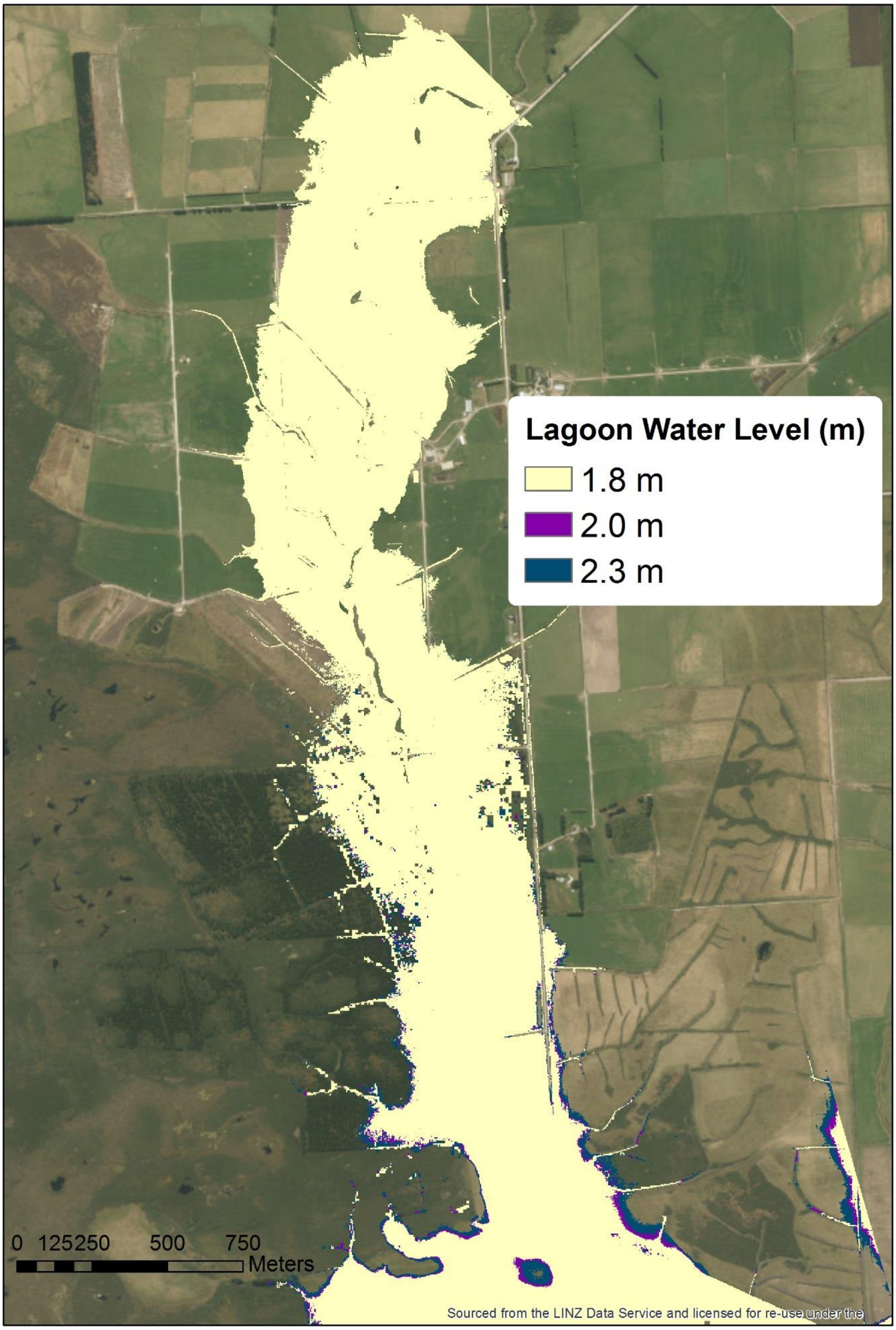

Figure H-4: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

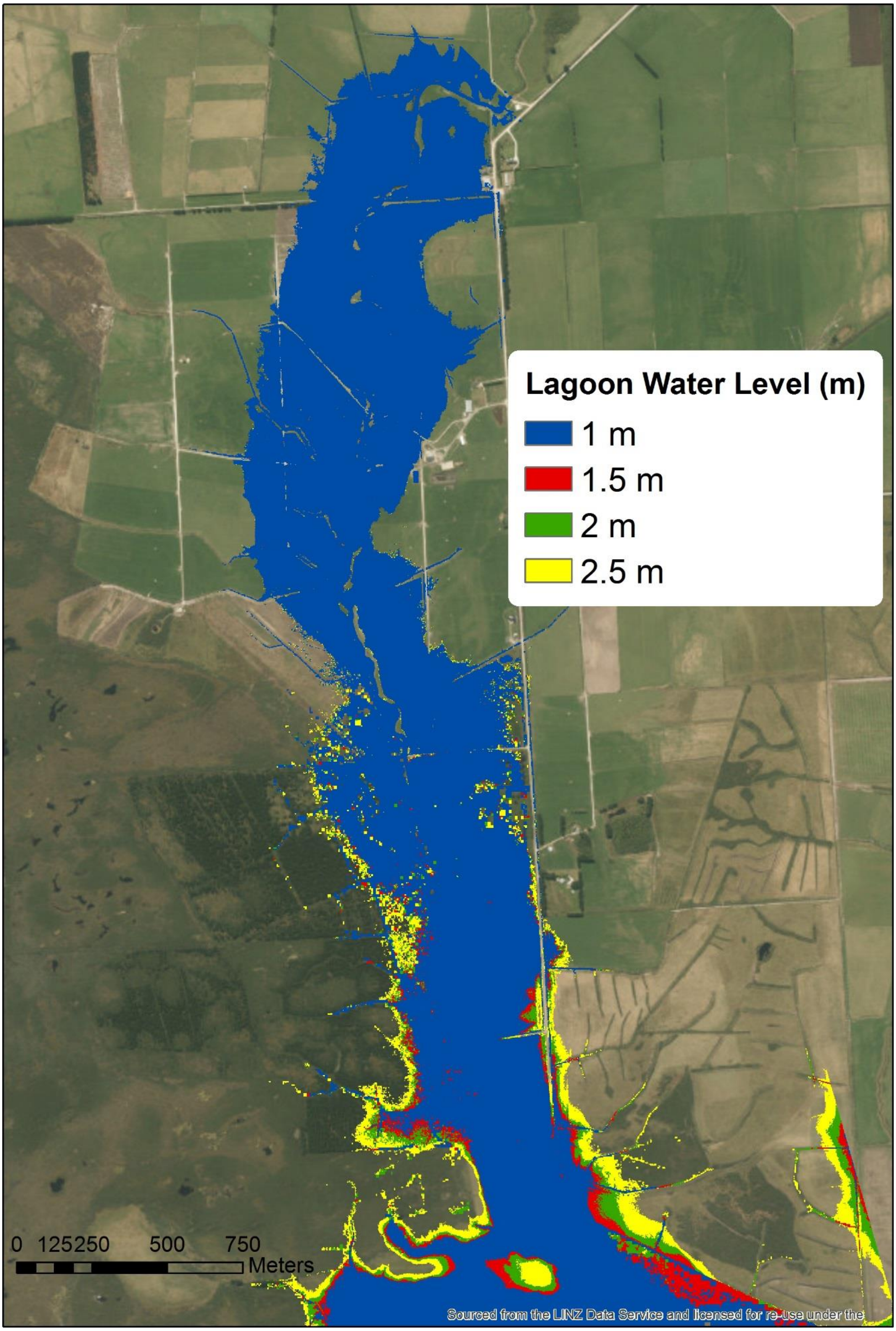

Figure H-5: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

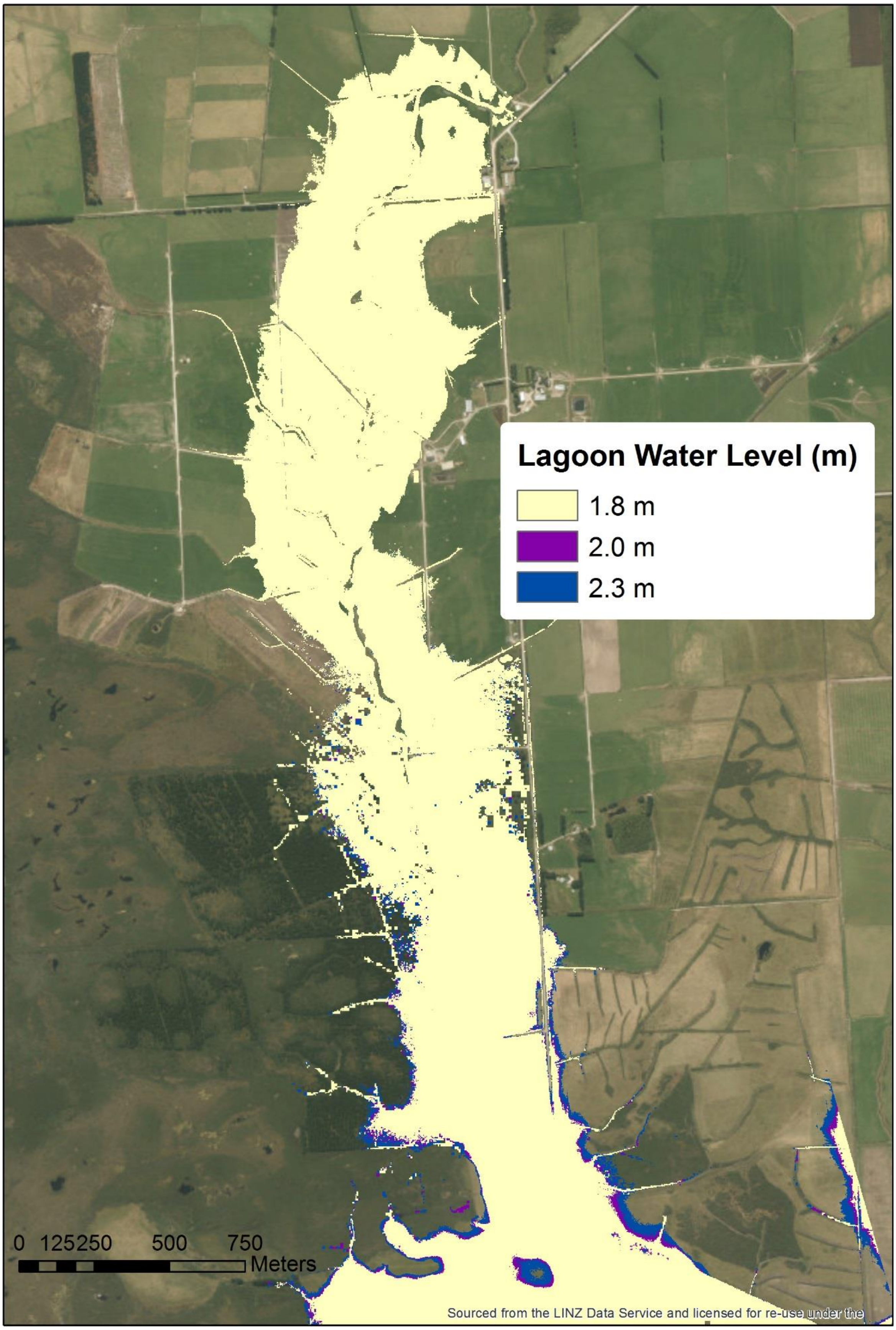

Figure H-6: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

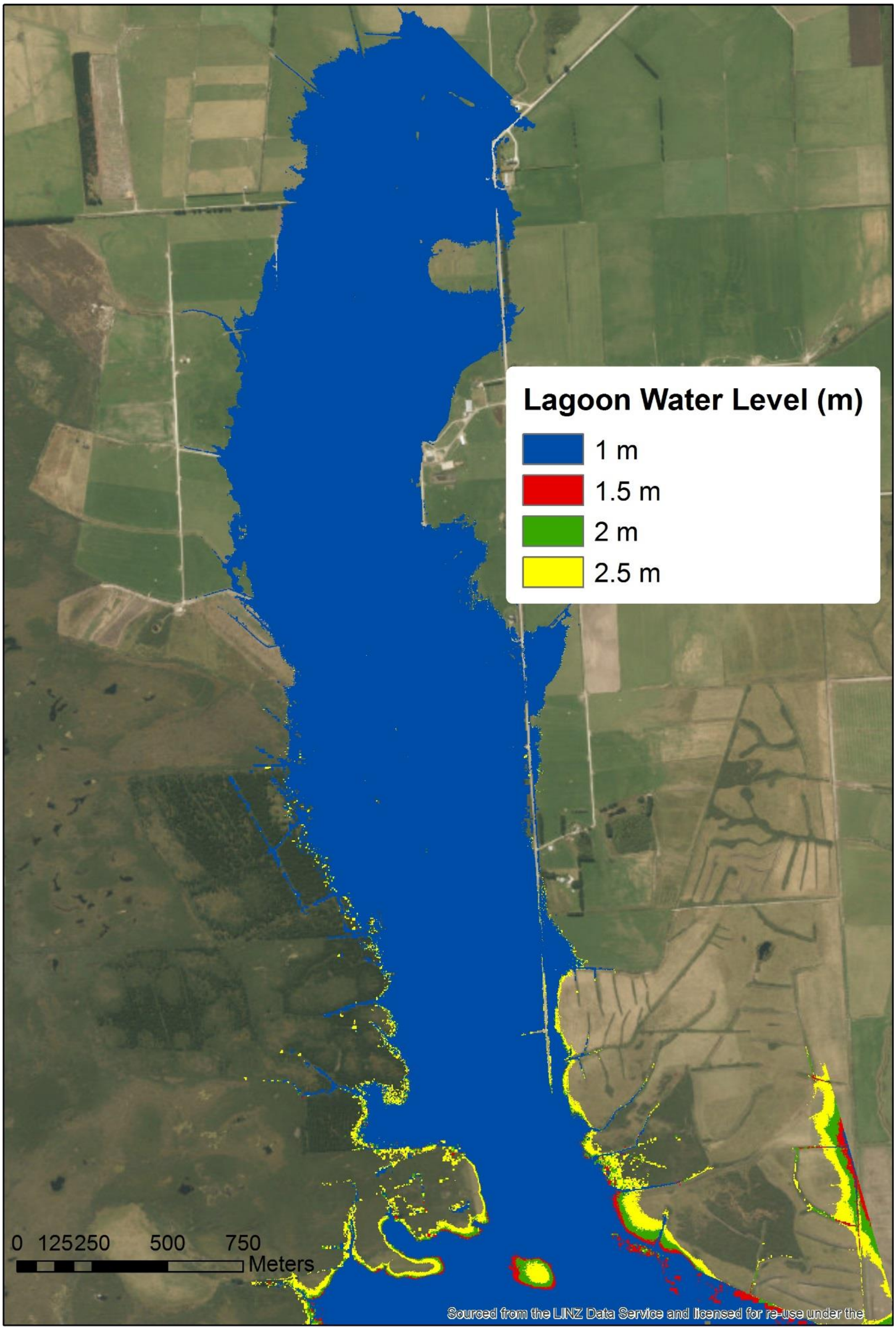

Figure H-7: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

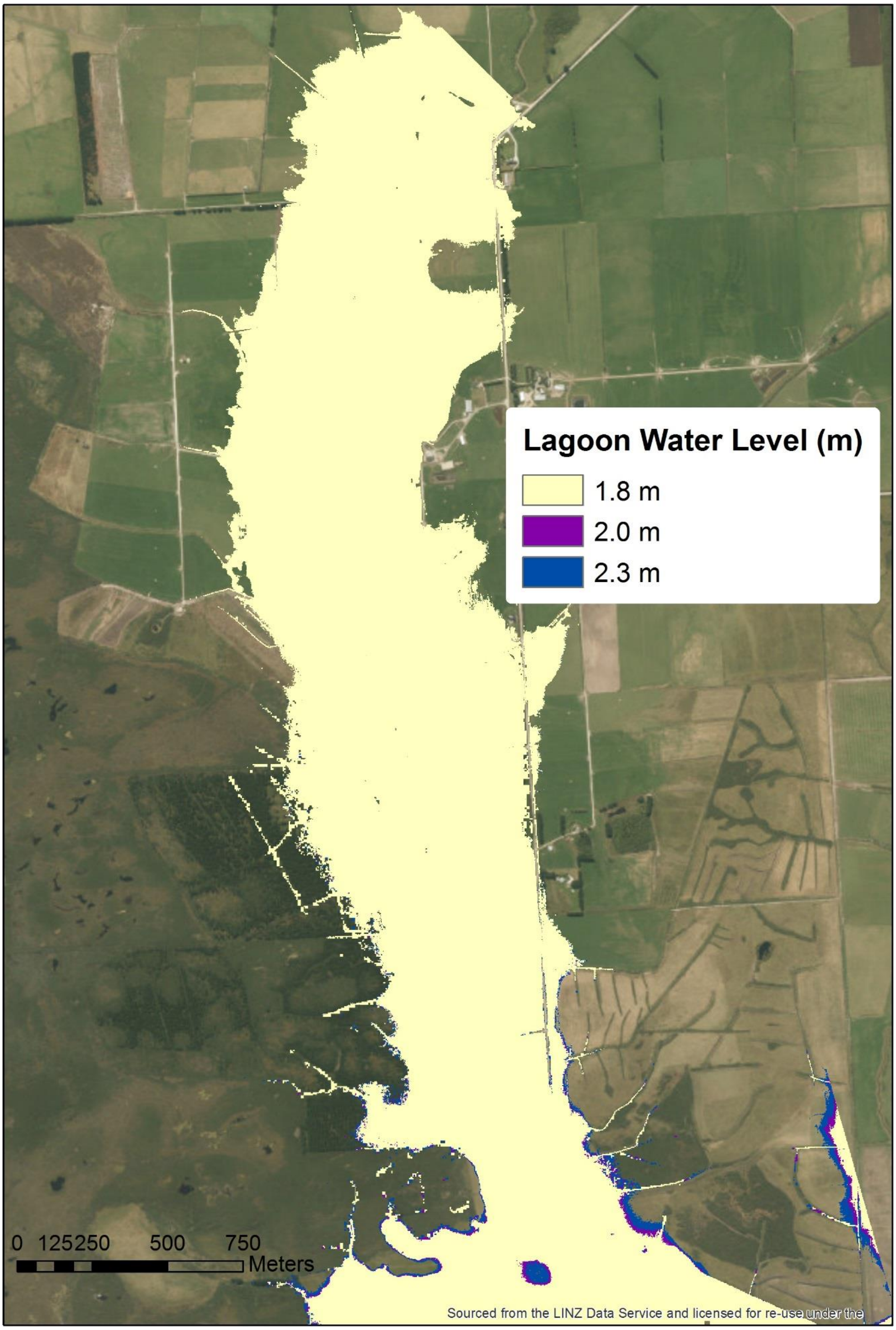

Figure H-8: Extent of land bordering Waituna Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile flow with a vegetated main channel.

Appendix I Moffat Creek potentially drainage affected land (2m threshold)

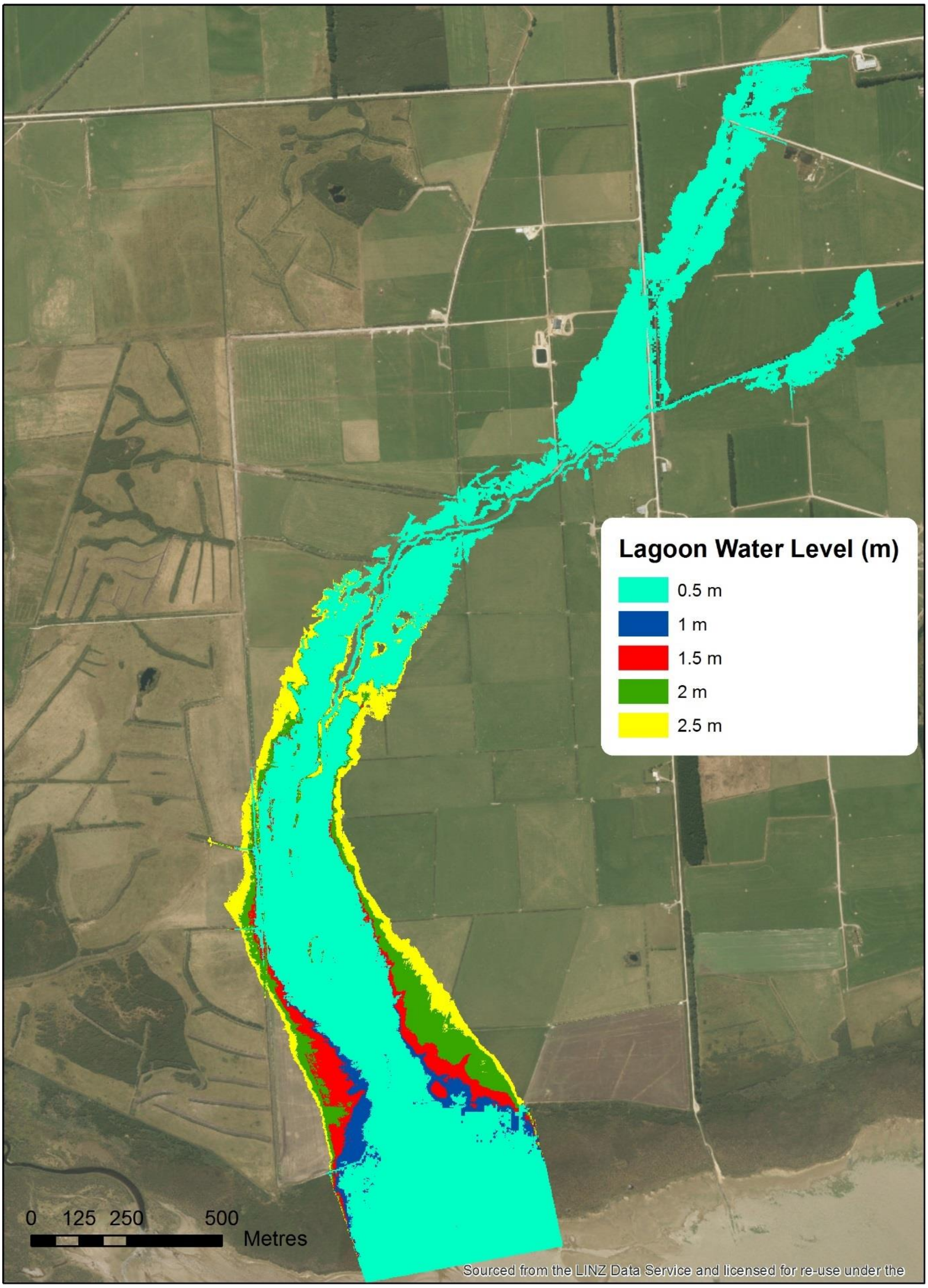

Figure I-1: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

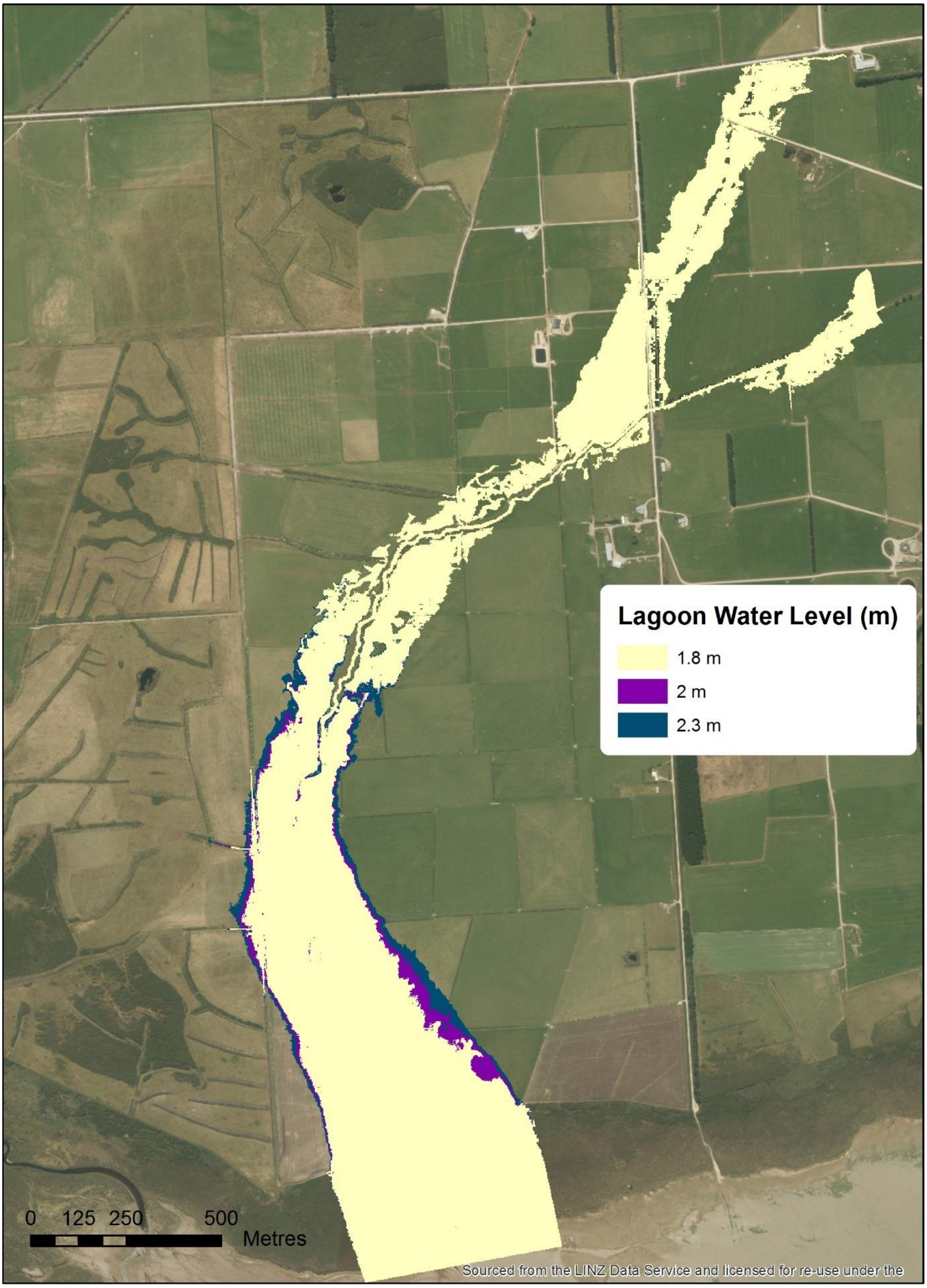

Figure I-2: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

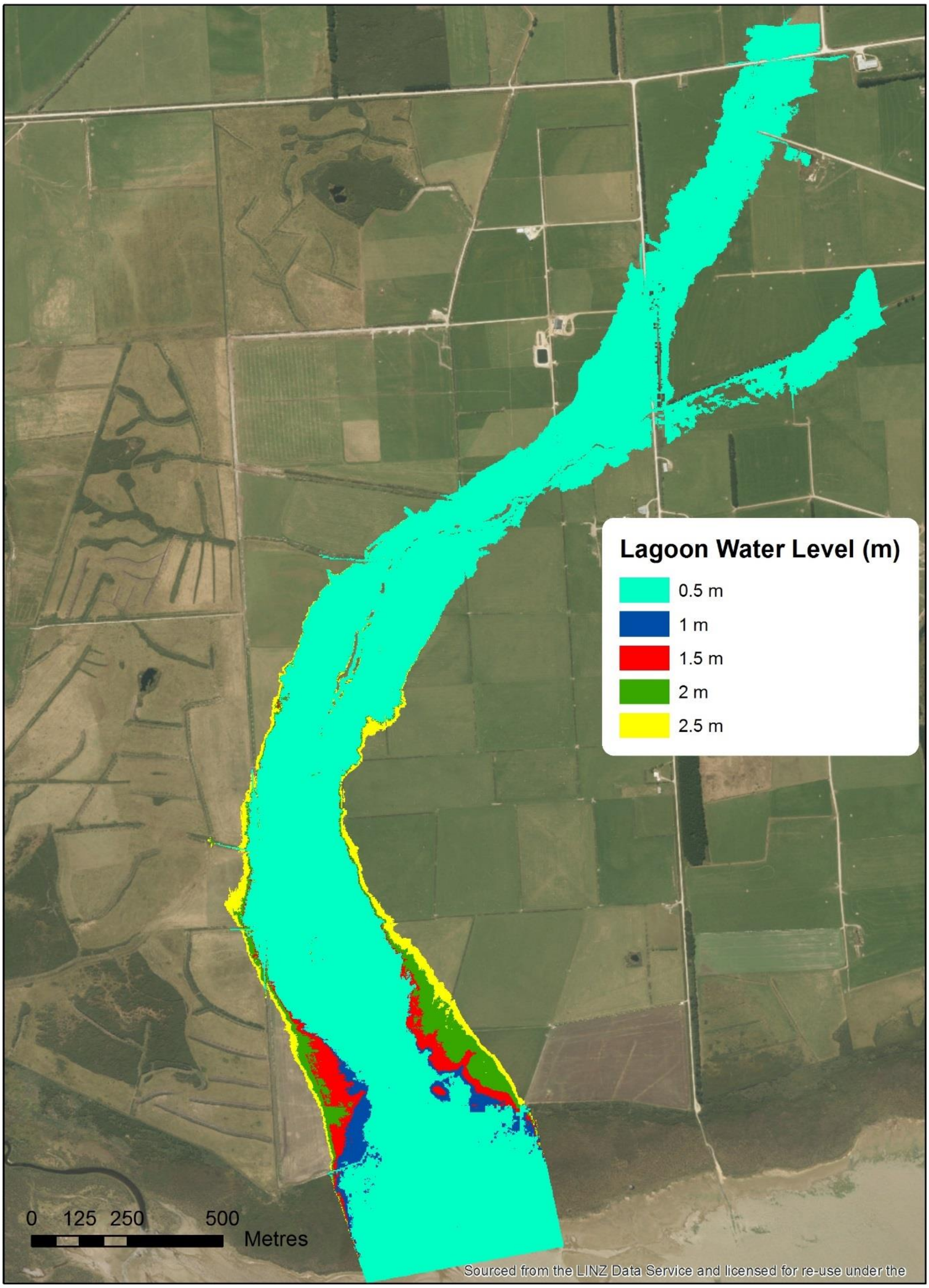

Figure I-3: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

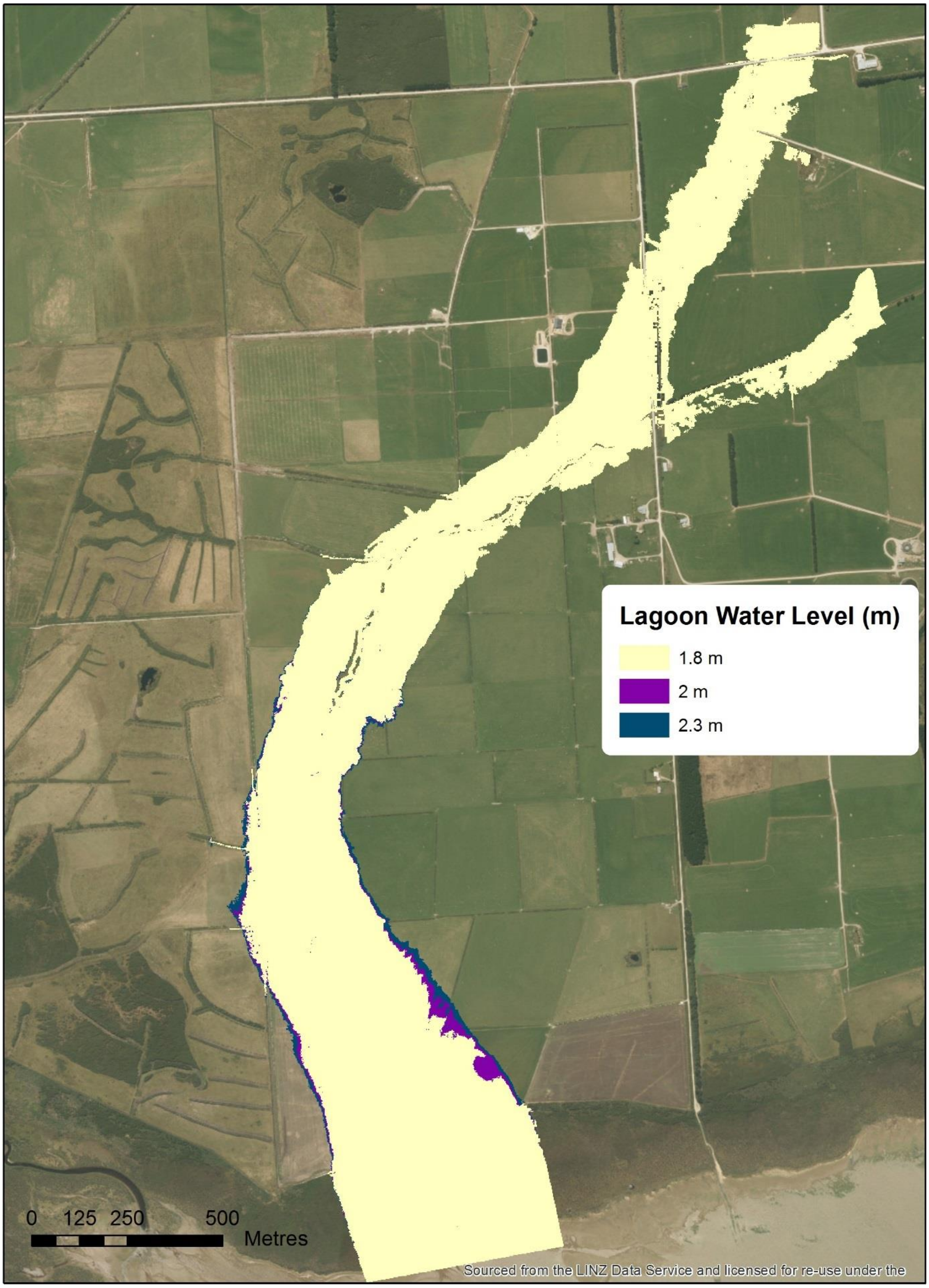

Figure I-4: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

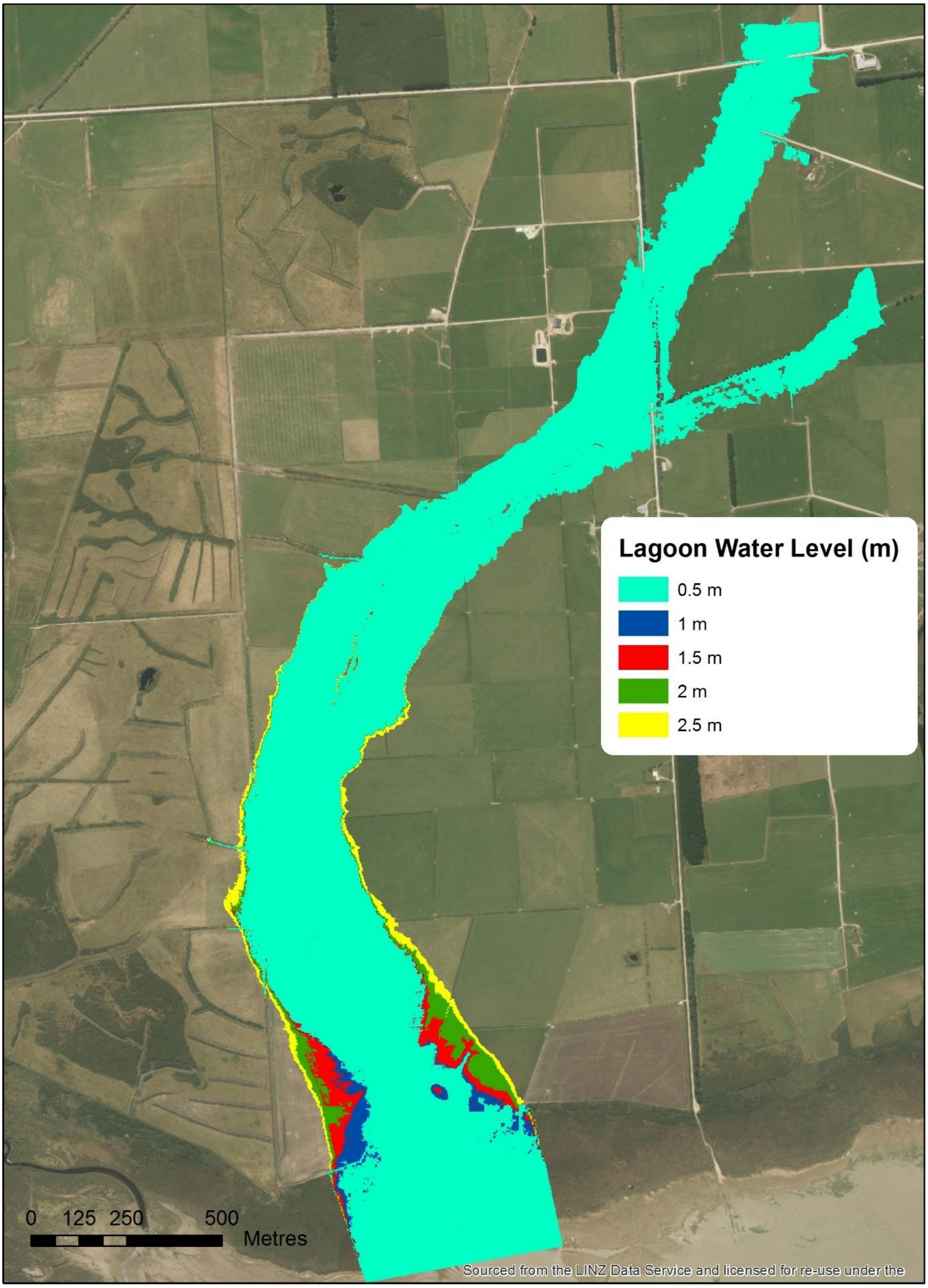

Figure I-5: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

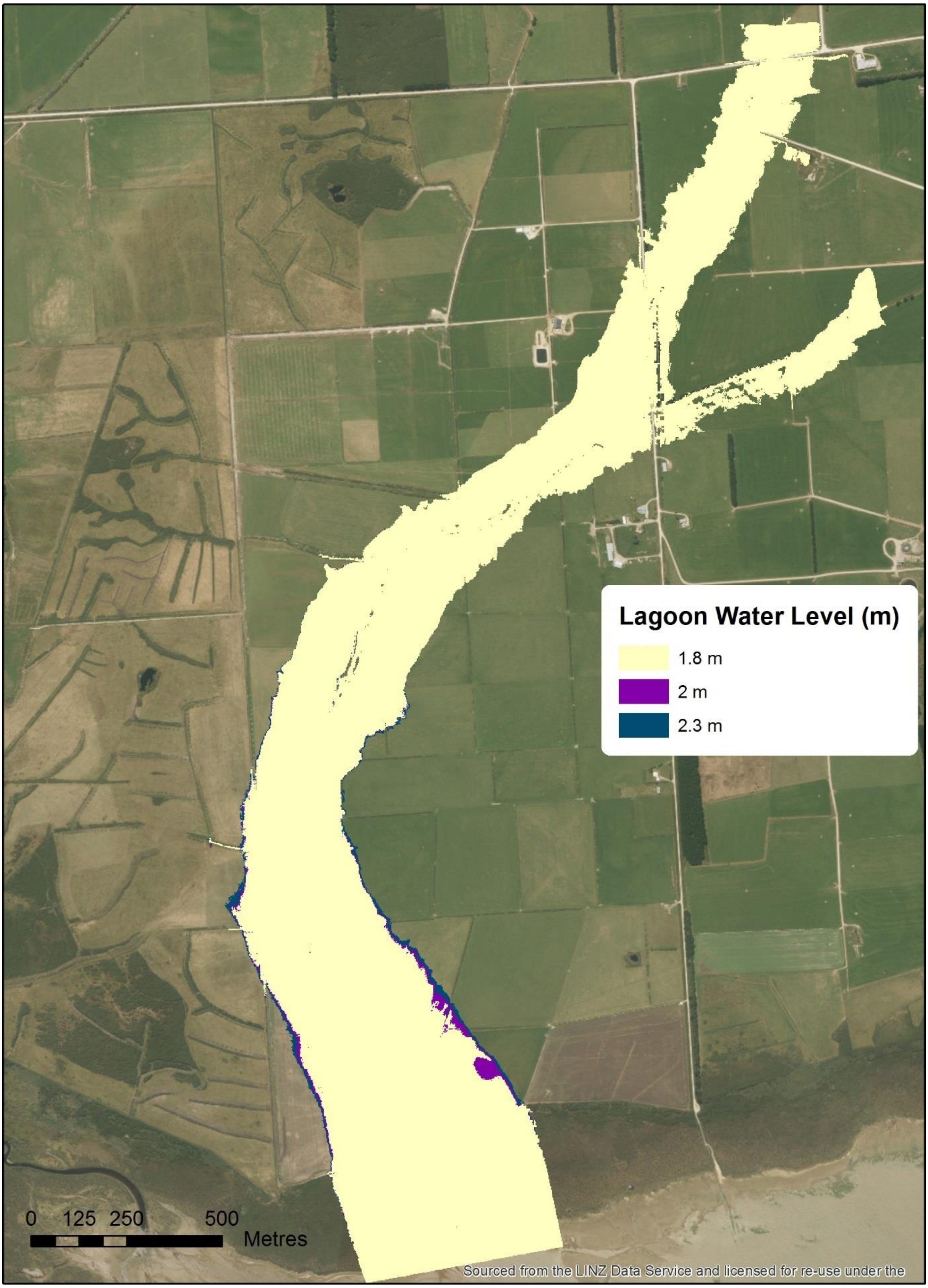

Figure I-6: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

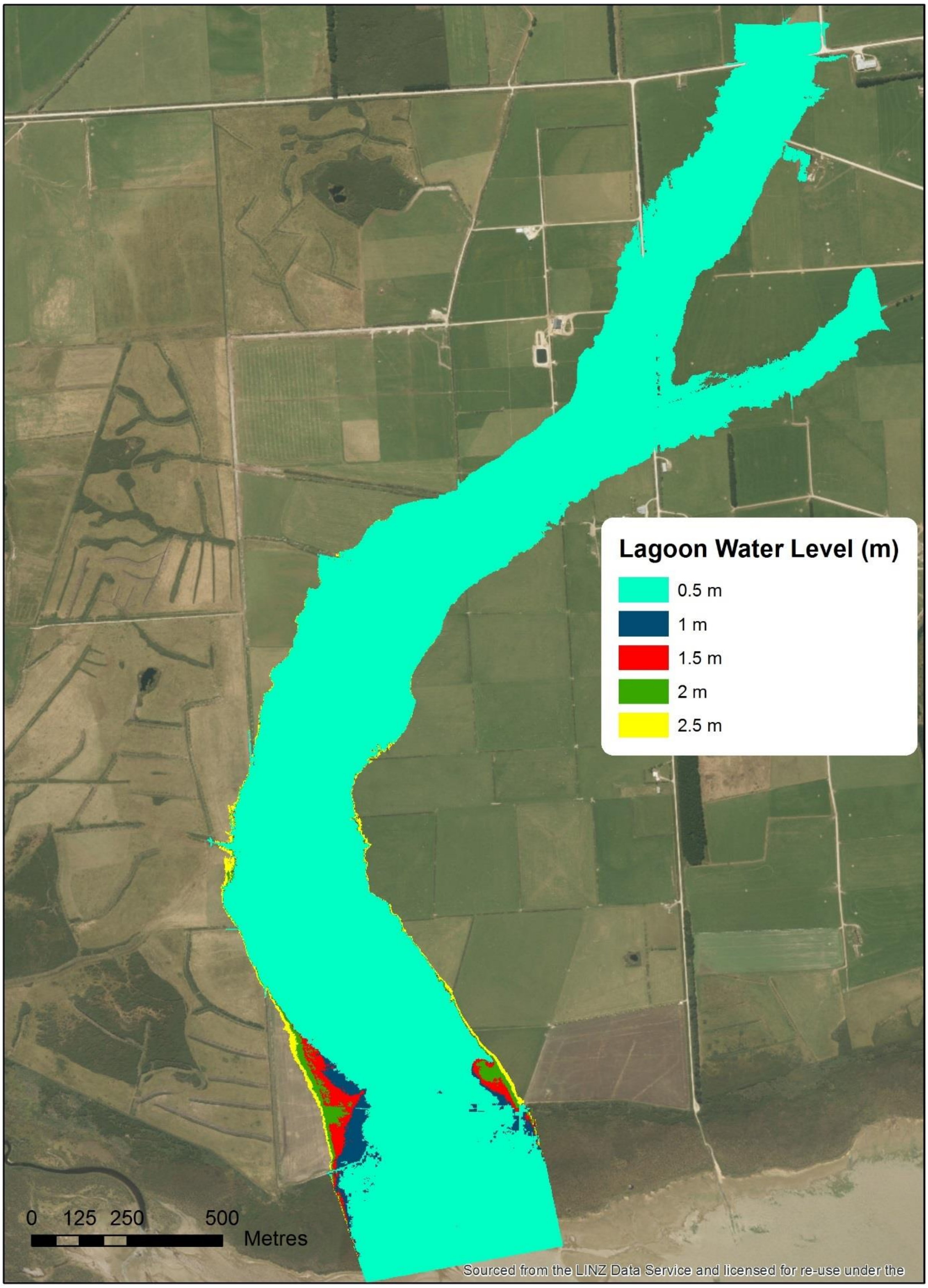

Figure I-7: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

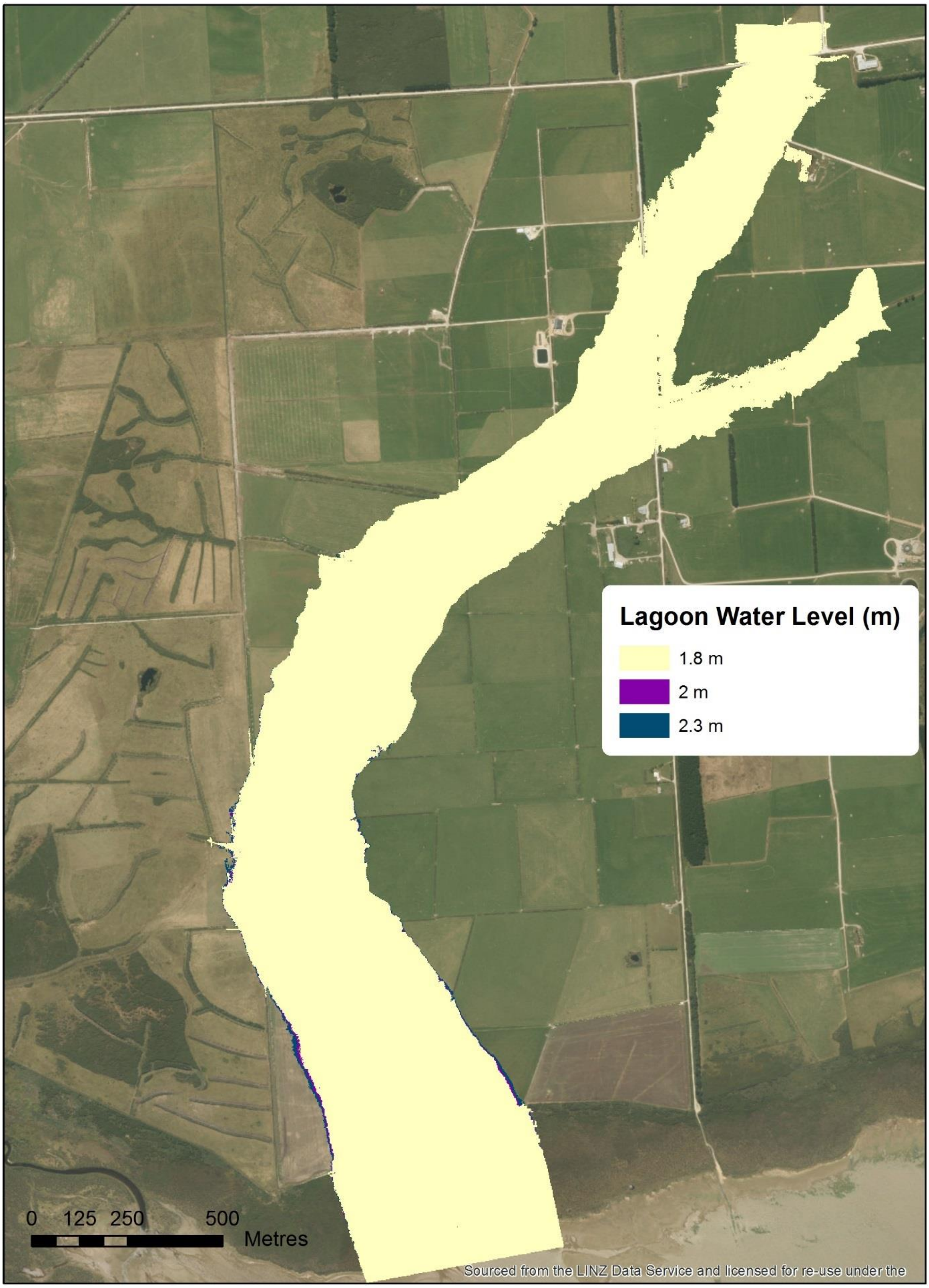

Figure I-8: Extent of land bordering Moffat Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile flow with a vegetated main channel.

Appendix J Carran Creek potentially drainage affected land (2m threshold)

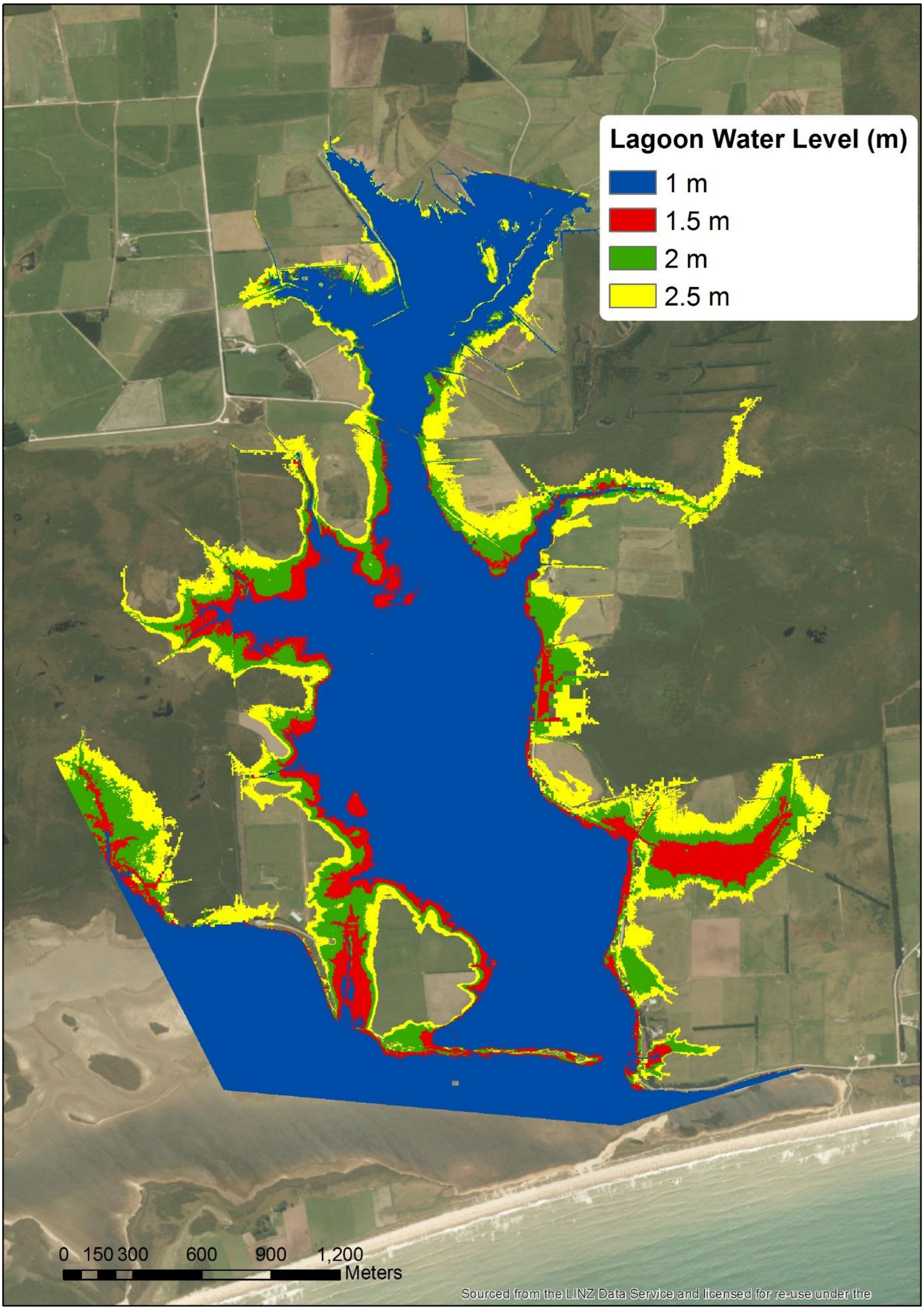

Figure J-1: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

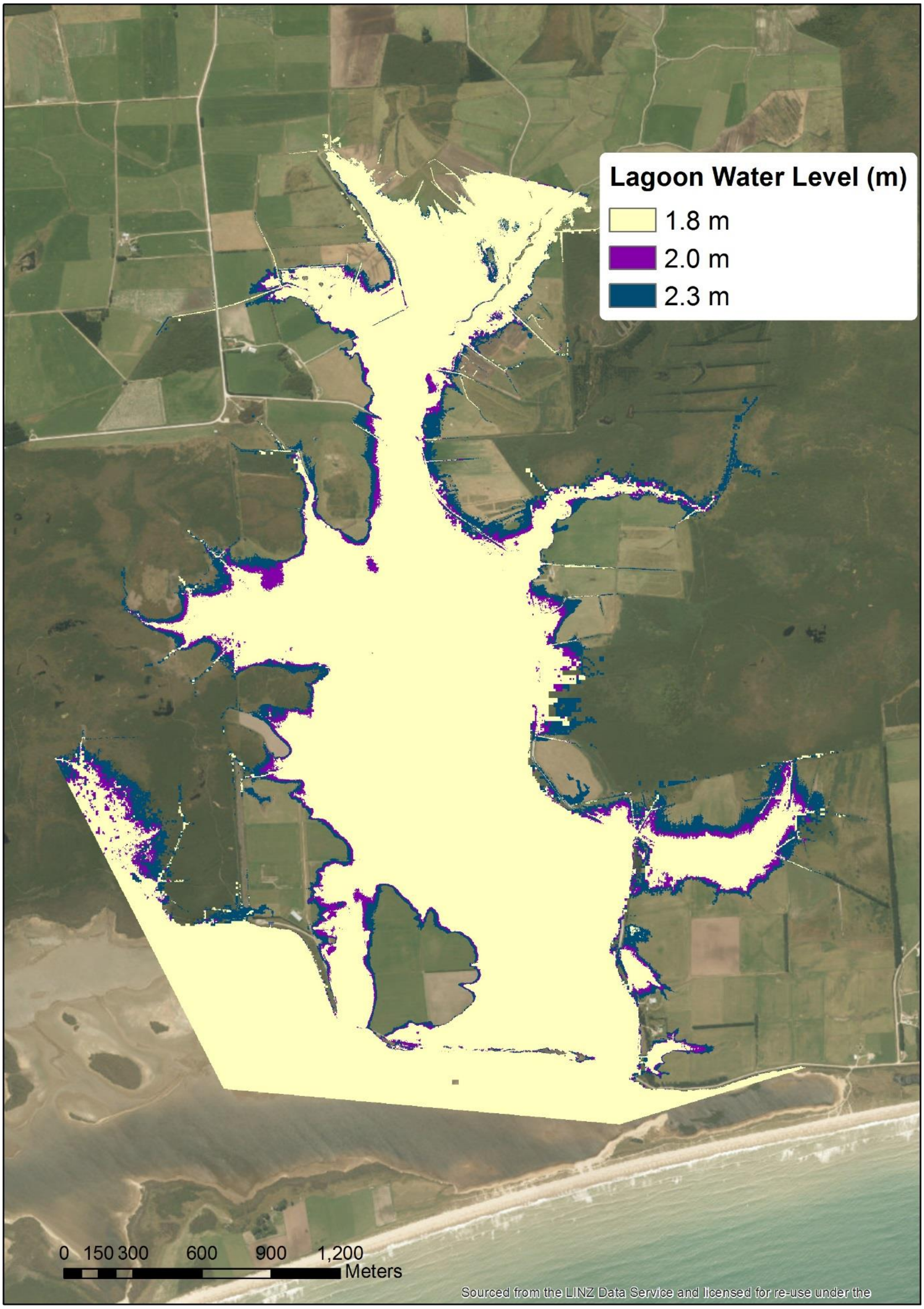

Figure J-2: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Cleared" models mean flow with a recently cleared main channel.

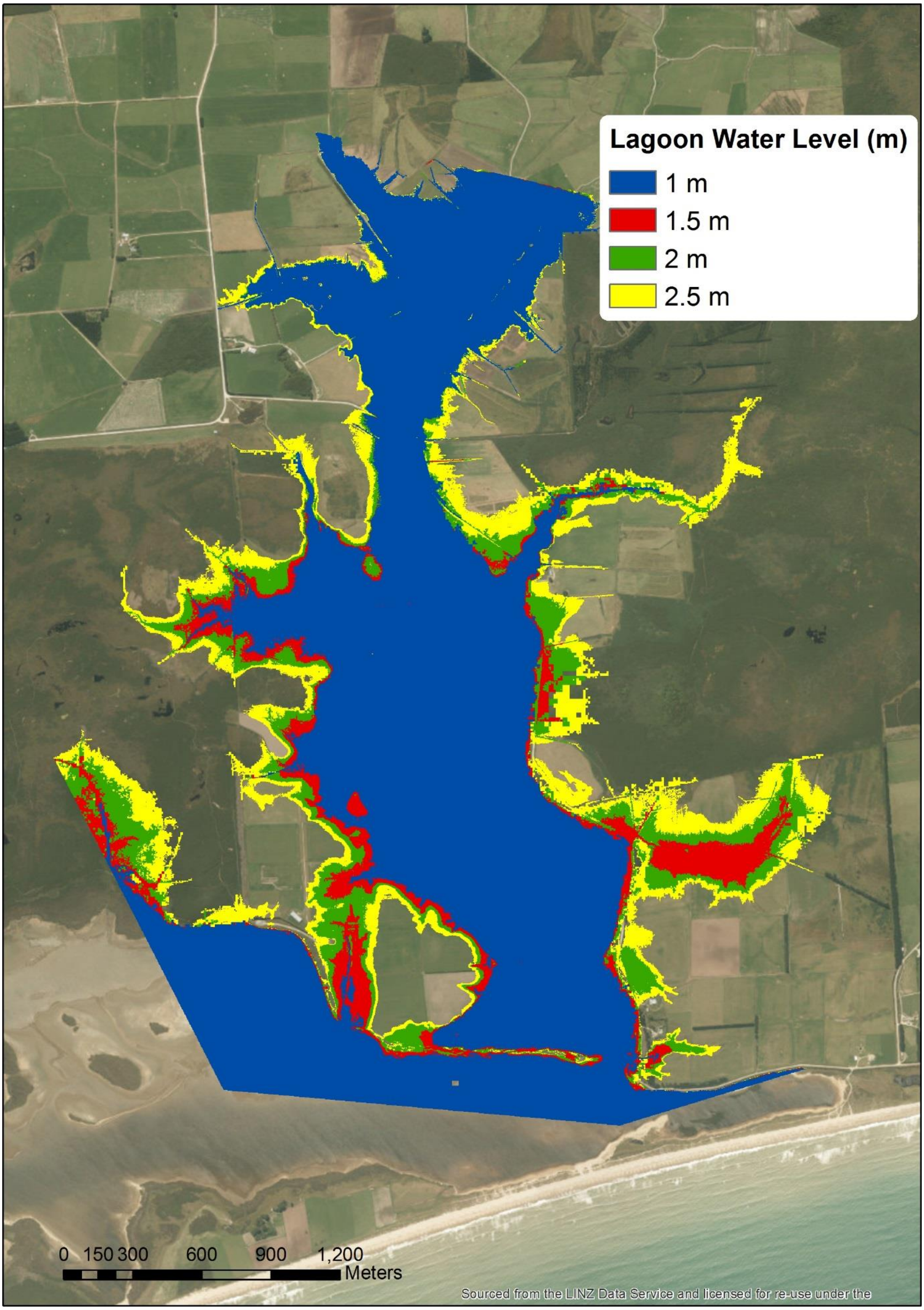

Figure J-3: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models the 90 percentile high flow with a recently cleared main channel.

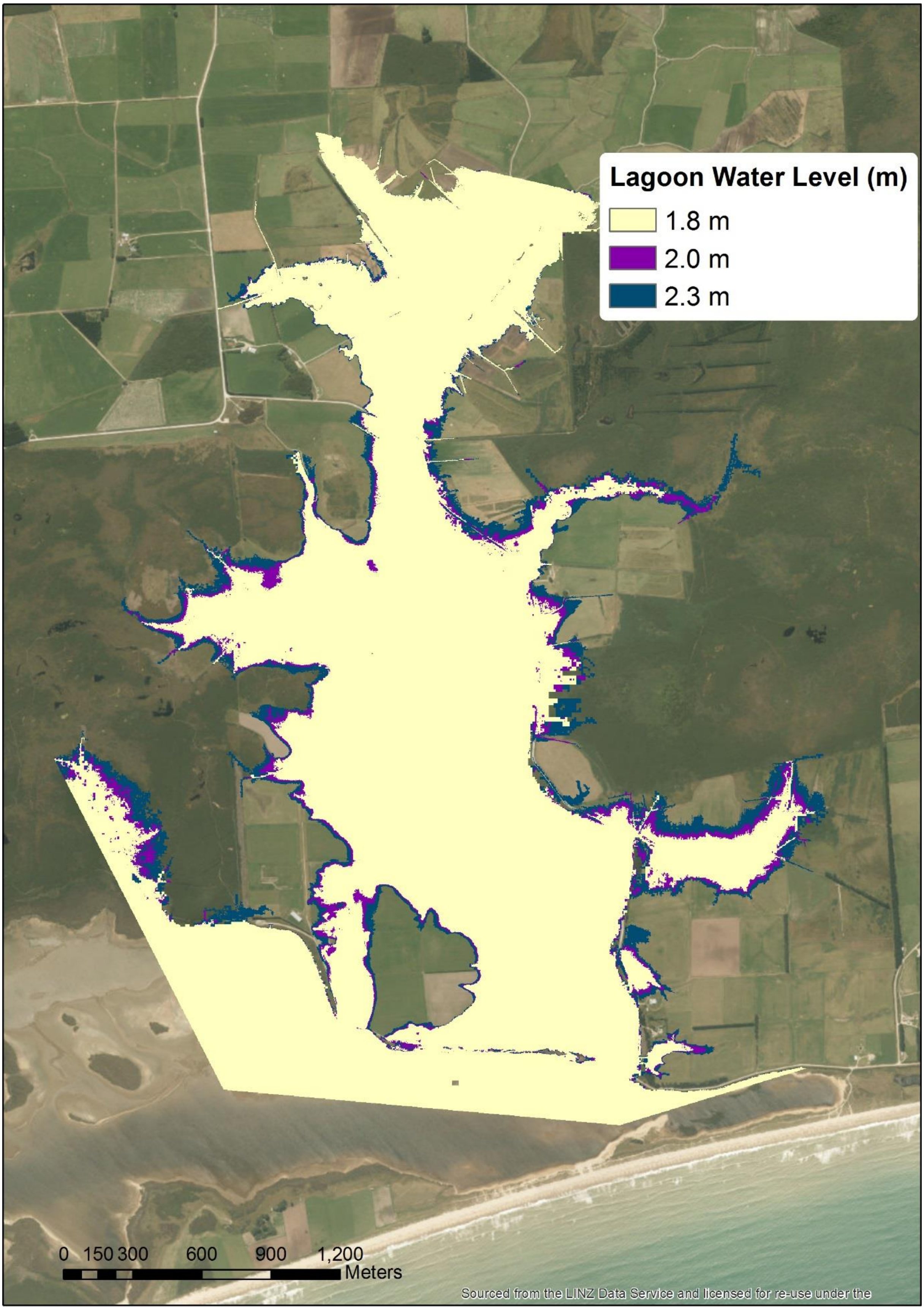

Figure J-4: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Cleared" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Cleared" models 90 percentile high flow with a recently cleared main channel.

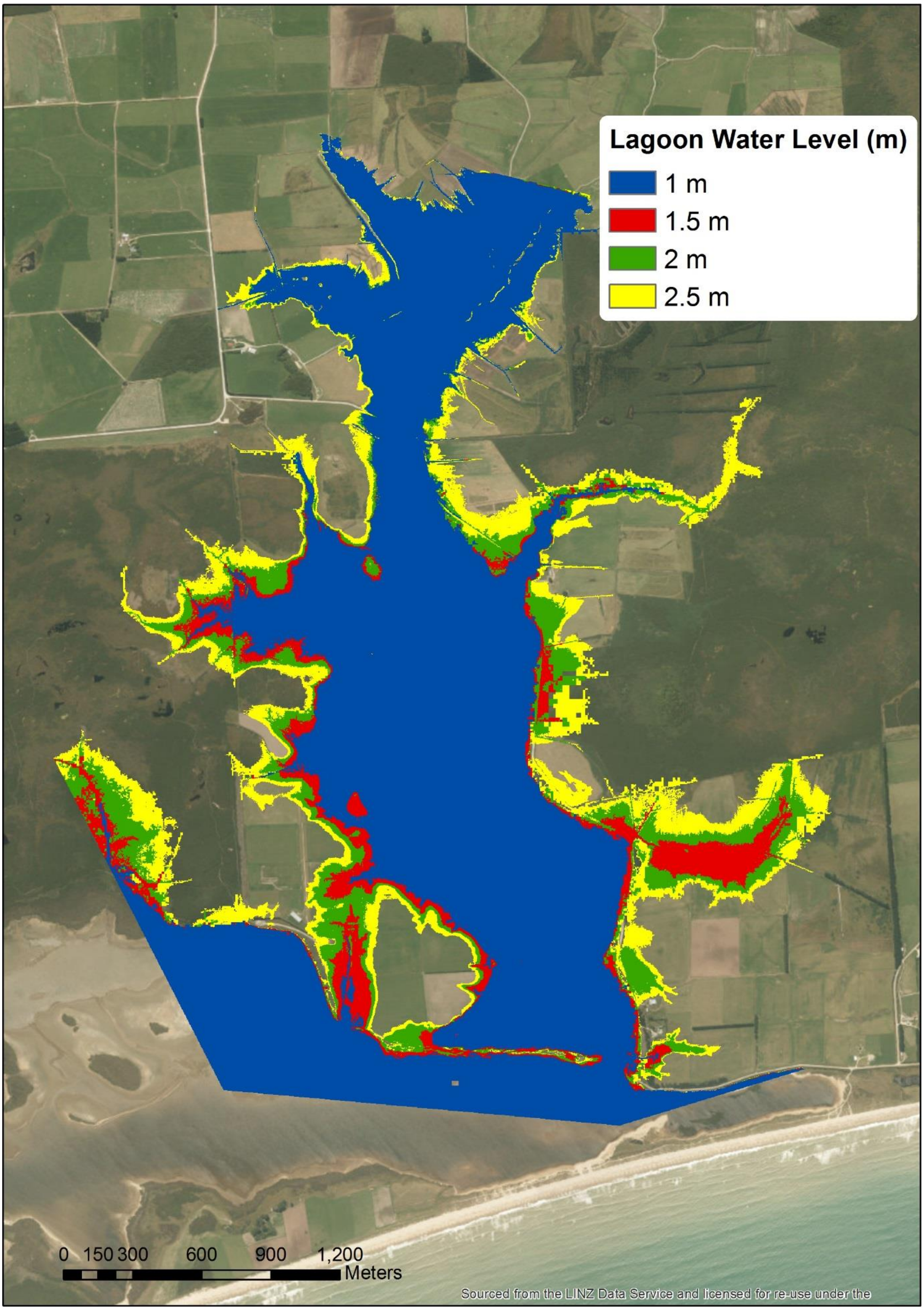

Figure J-5: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

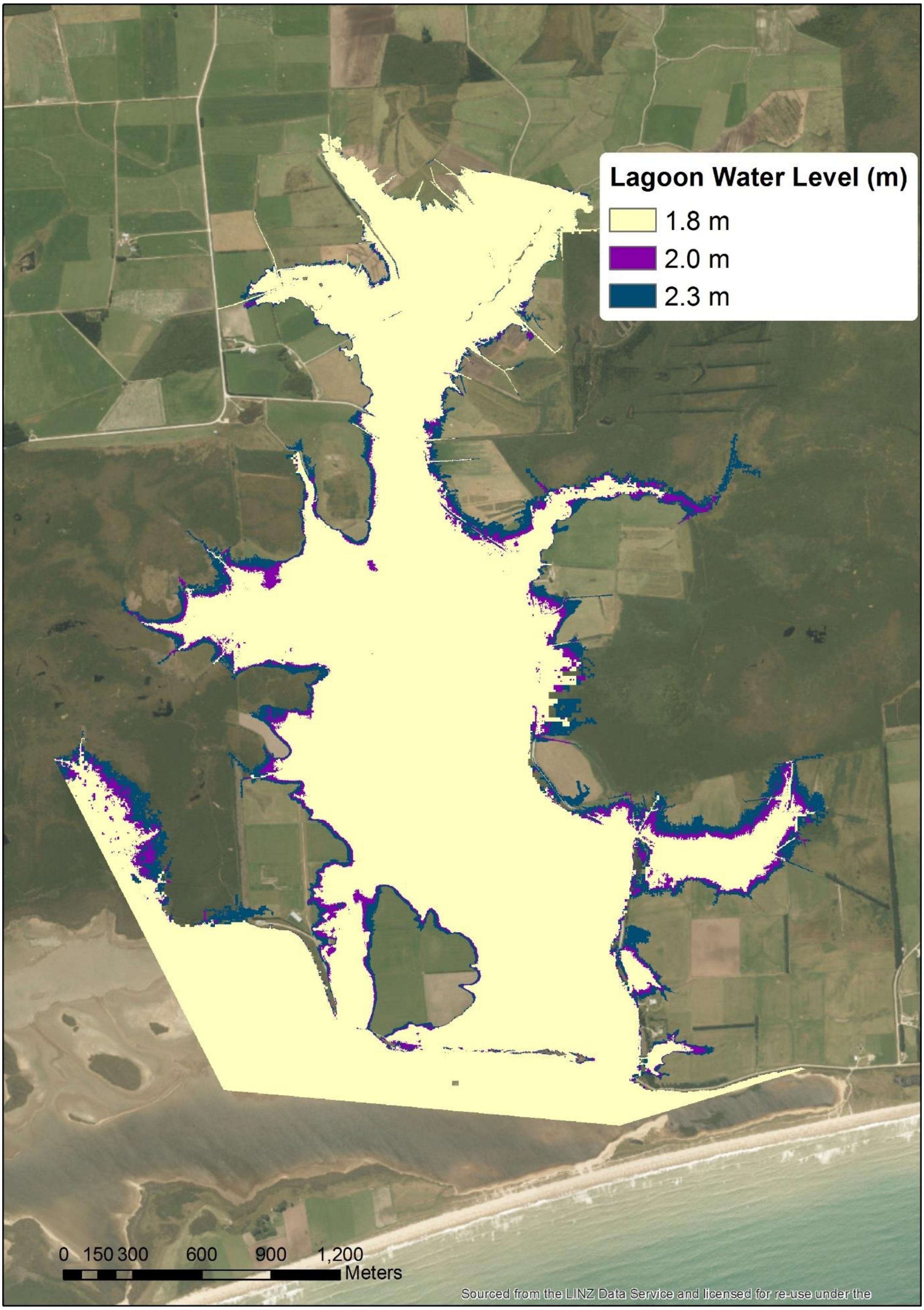

Figure J-6: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{mean}-Channel Vegetated" (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{mean}-Channel Vegetated" models mean flow with a vegetated main channel.

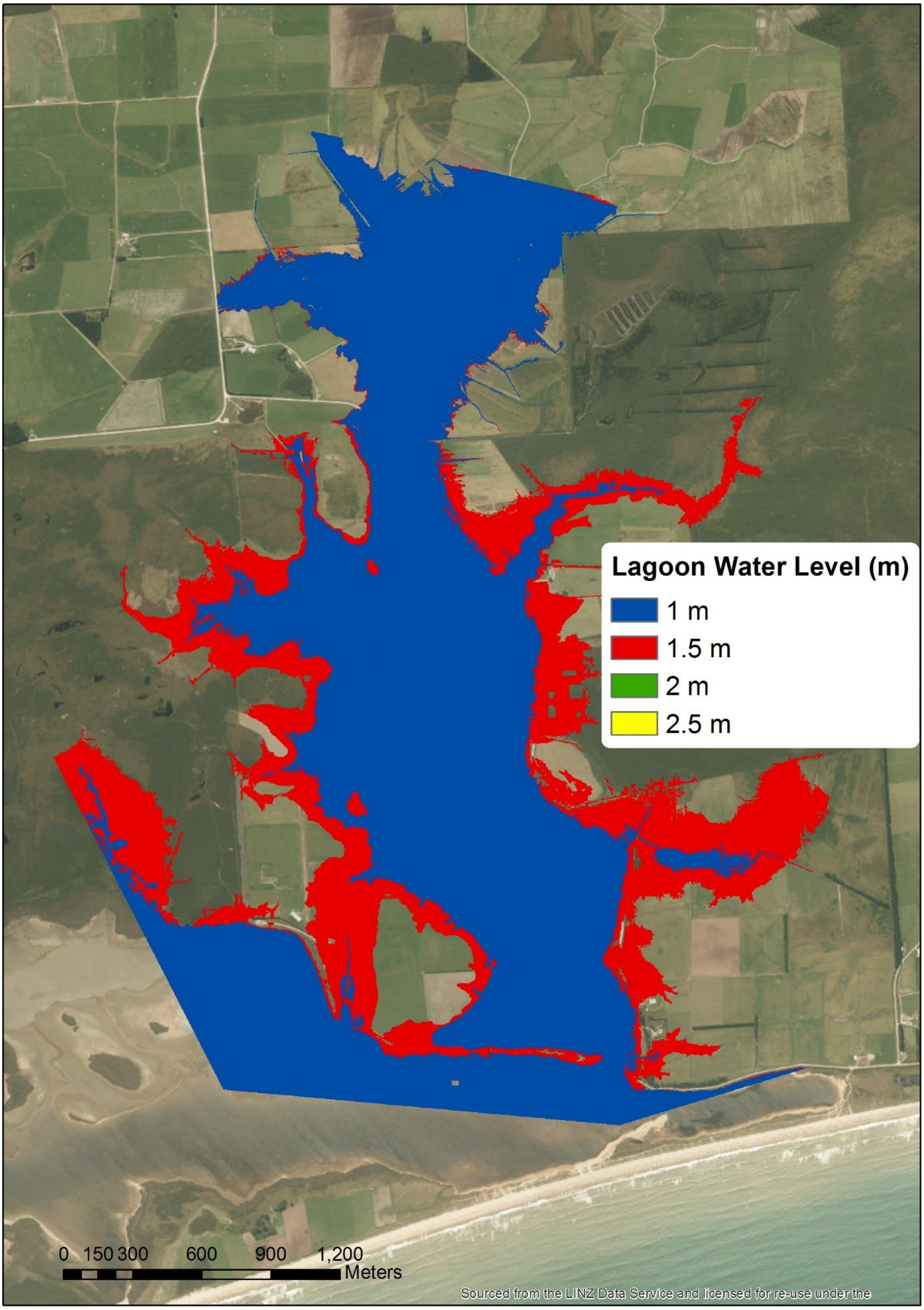

Figure J-7: Extent of land bordering Carran Creek that is potentially drainage affected under scenario "Q_{90}-Channel Vegetated". Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario "Q_{90}-Channel Vegetated" models the 90 percentile high flow with a vegetated main channel.

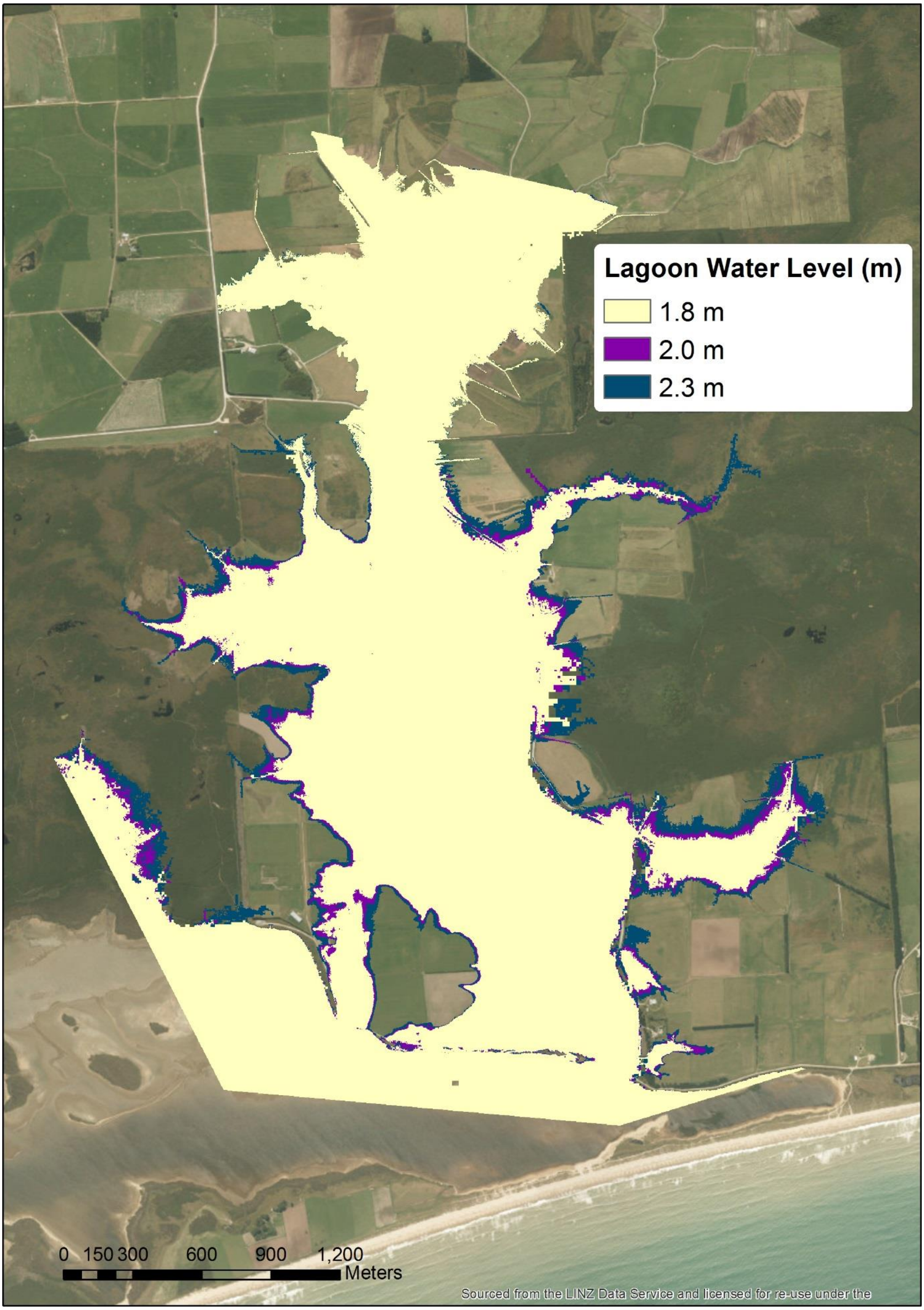

Figure J-8: Extent of land bordering Carran Creek that is potentially drainage affected under scenario “Q_{90}-Channel Vegetated” (specific lagoon levels of interest). Potentially drainage affected land is taken to be land adjacent to the channel with ground elevation less than 2.0 m above the channel water level. Scenario “Q_{90}-Channel Vegetated” models the 90 percentile high flow with a vegetated main channel.