Warkworth to Wellsford

Assessment of Coastal Sediment

July 2019

QUALITY ASSURANCE

Prepared by

Jacobs GHD Joint Venture in association with the National Institute of Water & Atmospheric Research Ltd (NIWA).

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EXECUTIVE SUMMARY

The NZ Transport Agency has initiated a Project to construct, operate and maintain a new state highway, from Warkworth near Woodcocks Road to the north of Te Hana near Maeneene Road. Earthworks associated with construction of the Project will change catchment derived sediment loads for rivers draining to both the eastern seaboard (Mahurangi Harbour) and western seaboard (Kaipara Harbour) of the Northland Peninsula.

The purpose of this report is to model the downstream fate of fine sediments discharged by the Project to the Hoteo River and Oruawharo River which drain into the Kaipara Harbour. Results from this report will inform the Marine Ecology Assessment (Bell and de Luca 2019) and the Project Water Assessment Report (Ridley et al. 2019). The fate of sediments discharged to Mahurangi Harbour is addressed in the Pūhoi to Warkworth Water Assessment Factual Report (Fountain and Innes, 2013).

This investigation does not address sand sized sediments because sediments released from the Project sediment control works are anticipated to be only fine sediments which remain in suspension after interception by stormwater control structures around construction zones.

The primary outputs of our work are maps and tables showing the amount and location of sediment predicted to be deposited on the seabed, and the suspended sediment concentration (SSC) at 1, 3 and 5 days after the start of sediment-discharge events. The maps and tables show background sediment deposition (before the Project) and compare it to the extra sedimentation induced by the Project, and show how the Project is predicted to elevate SSC above background levels. The catchment sediment loads input to the Harbour for the existing and predicted are detailed in the Catchment Sediment Report (Sands and Clay 2019).

The investigation was separated into two divisions, each associated with the fate of fine sediments discharged into the two river systems. The methodology of our assessment differs between each catchment because of the existing information and models available and the information required to support the Marine Ecology Assessment. The assessments were at a level of detail commensurate with the increase in sediment load to each catchment predicted by the Catchment Sediment Report and the scale of the receiving environment.

Hoteo River

The report provides the following information, which can be used to address ecological thresholds which are of specific relevance to the Marine Ecology Assessment:

- Maps of maximum SSC during discharge events associated with 10-year average recurrence interval (ARI) and 50-year ARI Hoteo River sediment loads.
- Maps of maximum continuous time where the SSC exceeds 0.08 kg/m^3
- Maps of sediment deposition depth at 3 and 5 days and after the start of the discharge event
- Area covered by sediment of depth 1–3, 3–5, 5–7, 7–10, and > 10 mm

- Maps of additional depth of sediment deposition arising from Project construction (i.e. the difference from pre-Project baseline conditions)
- Table of area where the SSC exceeds 0.08 kg/m^3 continuously for more than 72 hours.
- Table of area with sediment deposition > 3 mm

We used a sediment-transport model to simulate the short-term (1 week) effect of increased sediment loads for 10-year average recurrence interval (ARI) and 50-year ARI sediment discharge events from the Hoteo River into the Kaipara Harbour under three wind conditions (calm, southwest and northeast). The model predictions of sediment deposition rate near the mouth of the Hoteo River are consistent with radioisotopic dating of sediment cores (Swales et al. 2011, 2016), and the spatial pattern of sedimentation is consistent with previous modelling studies (Pritchard et al. 2012, 2013; Green et al. 2017) and sediment source tracing core samples (Gibbs et al. 2012).

Short-term events

In the short-term modelling (1-week model period) the sediment plumes for all simulations are quickly dispersed or settle to the sea bed at a rate dependent on the wind and wave conditions, with a small (8%) proportion of sediment leaving the Harbour mouth on the ebb tide and lost offshore. All simulations show the additional sediment discharged by the Project results in a small increase to SSC above baseline conditions and a small increase to sediment deposition above baseline conditions.

The additional sediment arising from Project construction results in SSC exceeding the concentration-time threshold of ≥ 0.08 kg/m^3 for ≥ 72 hours for a 50-year ARI discharge with NE and SW wind conditions. No other modelled events exceed this concentration-time threshold. In these cases, an area of 3.5 ha exceeds the threshold for the 50-year ARI NE wind condition, which is a 1.4 ha increase above the baseline conditions. And an area of 1.4 ha exceeds the threshold for the 50-year ARI SW wind condition which is a 1.4 ha increase above the baseline which does not exceed the threshold in these conditions.

The additional sediment arising from Project earthworks causes the area and depth of sediment deposited in the Harbour to increase. The area of harbour receiving more than 3 mm of deposition in the baseline is 52–145 ha for the 10-year ARI events and 156–237 ha for the 50-year ARI events. These areas increase due to construction by 4–5.5 ha (3–10%) in the 10-year ARI scenario and 11–24 ha (6–15%) in the 50-year ARI scenario.

The model cells which *only* exceed 3 mm of total deposition during Project earthworks are generally on the fringe of the deposition footprints within 2 km of the Hoteo River mouth for the 10-year ARI scenarios and also spreading into each of the small sheltered sub-inlets flanking the Tauhoa River inlet and the Kakarai intertidal flats in the 50-year ARI scenario The baseline total deposition in these fringing areas is 2.8–2.9 mm but increase by 0.19-0.23 mm for the 10-year ARI scenarios and 0.37–0.41 mm for the 50-year ARI scenario (Table 12). The maximum additional deposition in any of the fringing model cells is 0.5 mm during the 50-year ARI SW scenario. Deposition will not be uniform across these areas, with preferential deposition localised to areas of decelerating flow and within the most sheltered and vegetated areas.

Long term

The mouth of the Hoteo River is a depositional environment for sediment with a history of rapid infilling by fine sediments. The deposition footprints of sediment discharge from the Hoteo River is most prominent in the upper intertidal flats and sub-inlets flanking the eastern shoreline near the Hoteo River Mouth, the tidal flats near Papakanui River and Tauhoa River estuary and near Moturimu island.

We assess that sediment discharged from the Hoteo River contributes in the order of 3.4 – 10 mm/year to the existing annual sedimentation rate (ASR) on the Kakarai Flats near the Hoteo River Mouth, with the proportion of locally sourced sediment increasing with distance upstream. The additional deposition arising from the Project earthworks is in the order of 0.034 – 0.1 mm per year, commensurate with 0.9% (228 t/year for the 6-year earthworks period) increase to annual average sediment load from the Hoteo River (25,600 t/year). The additional sediment load is also small relative to the natural variability in sediment load (a standard deviation of 9,737 t/year as over the 40-year simulation period). Hence, the cumulative effects of the Project on the long-term sediment deposition rates are negligible, well within natural annual variability and would be nearly impossible to measure in the field or attribute to the Project.

Oruawharo River

We carried out a literature review, site visit and assessment of the likely depositional footprint for the Oruawharo River estuary of the northern Kaipara Harbour, specifically including Maeneene Creek and Te Hana Creek. The Oruawharo River estuary of the Kaipara Harbour is a depositional environment, with a history of rapid infilling by fine sediments.

Short-term events

For the Oruawharo River, we used a heuristic approach to consider the potential effects of sediment retention in the upper estuaries during short-term events. Overall, 5% of locally discharged sediment is anticipated to leave the sub-estuary with the remainder distributed around the estuary by tidal currents and wind-waves to be deposited in sheltered areas. Irrespective of the proportion of sediment retained close to the source or dispersed widely, the deposition of sediment arising from the Project will remain below the ecological threshold of 3 mm per event at all areas in the Oruawharo Arm. The maximum average deposition is 1.17 mm in the Te Hana Creek sub-estuary for the baseline 50-year ARI event. The additional sediment from Project earthworks increases deposition to between 0.02 mm and 0.26 mm for the 50-year ARI events, and less than 0.1 mm for both the 10- and 2-year ARI events. Oruawharo River estuary. We expect that the sediment load resulting from the Project remain below the concentration-time threshold of 80 g/m^3 for 72 hours because of flood-flow flushing and dilution around the estuary. Hence, the increase in sediment load arising from Project construction is not expected to result in SSC levels substantially higher than for background events or for elevated SSC to persist for a longer duration than background events.

Long-term

Over the long-term (6 year) period of Project earthworks, the 0.16% per year increase in sediment load into the headwaters of the Oruawharo River will result in small increases (0.02

mm/year) over the wider estuary) to existing sediment accumulation rates. This is a negligible increase to the existing sedimentation rate when considering all sediment sources (is 6 mm/year).

In both the short-term and long-term situations, sediment accumulation is not uniformly distributed in the estuary. Areas which will receive increased deposition due to Project construction are those of the existing primary depositional areas, but at a fractionally higher rate. These areas include the sheltered areas (intertidal flats, sheltered inlets) and around the fringes of exposed reaches (Hargreaves Basin). The highest deposition rates are expected within the most sheltered mangrove stands. Substantial deposition of fine sediment is not anticipated in exposed open reaches (Hargreaves Basin) or areas scoured by rapid currents (entrance throat and the main sub-tidal channel).

1 INTRODUCTION

1.1 Overview of the Project

The NZ Transport Agency (Transport Agency) is lodging a Notice of Requirement (NoR) and applications for resource consent (collectively referred to as “the Application”) for the Warkworth to Wellsford Project (the Project).

This report is part of a suite of technical assessments prepared to inform the Assessment of Effects on the Environment (AEE) and to support the Application. This assessment report addresses the potential coastal sediment effects arising from the Project to inform the Marine Ecology Assessment. The assessment considers the effects of an Indicative Alignment and other potential effects that could occur if that alignment shifts within the proposed designation boundary when the design is finalised in the future.

1.2 Project description

The Project involves the construction, operation and maintenance of a new four lane state highway. The route is approximately 26 km long. As shown in Figure 1, the Project commences at the interface with the Pūhoi to Warkworth project (P-Wk) near Woodcocks Road. It passes to the west of the existing State Highway 1 (SH1) alignment near The Dome, before crossing SH1 just south of the Hoteo River. North of the Hoteo River the Project passes to the east of Wellsford and Te Hana, bypassing these centres. The Project ties into the existing SH1 to the north of Te Hana near Maeneene Road.

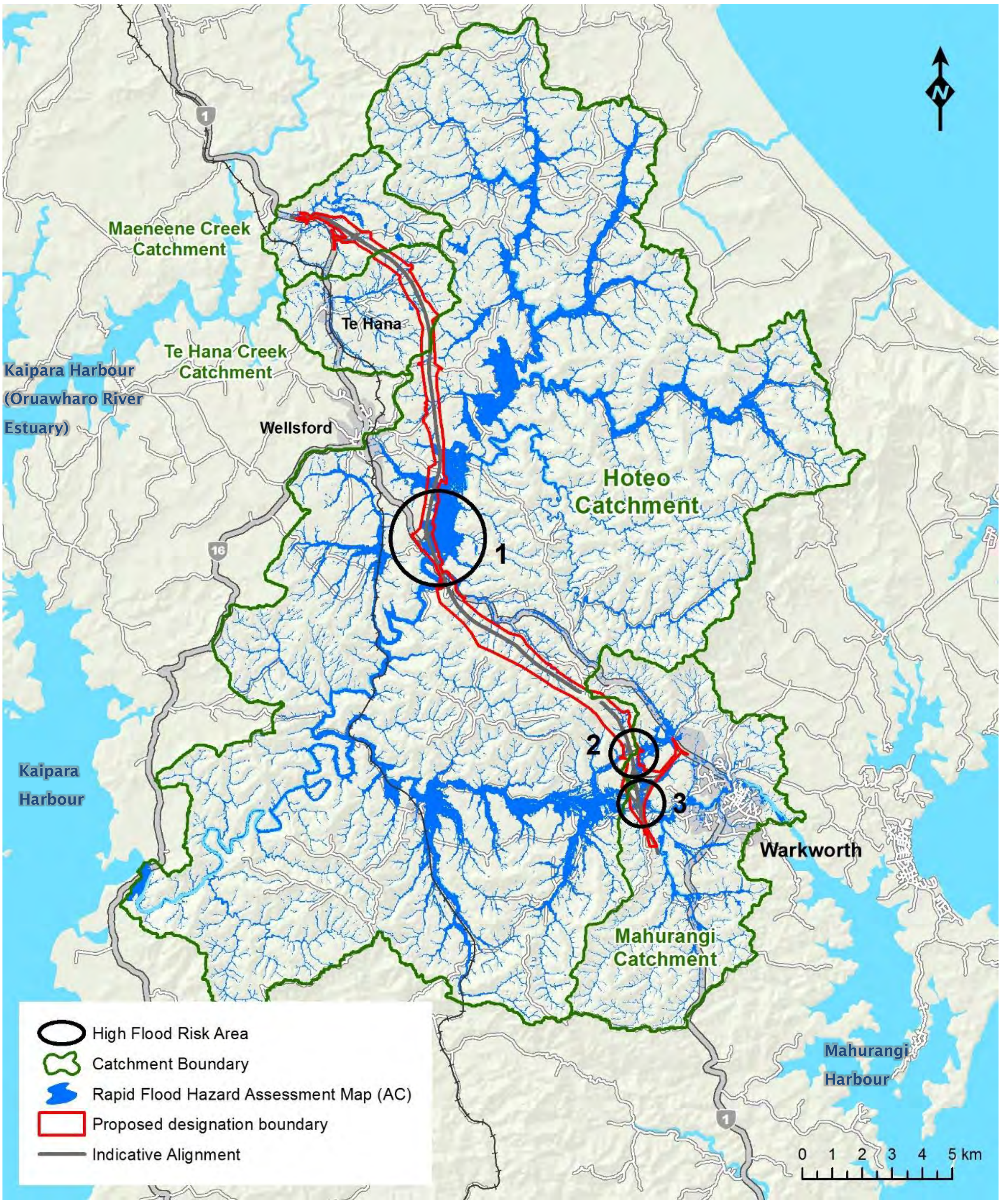

Figure 1: Indicative Alignment of the Project and Major Catchments [*Source*: Jacobs].

The Indicative Alignment shown on the Project drawings is a preliminary alignment for a state highway that could be constructed within the proposed designation boundary. The Indicative Alignment has been prepared for assessment purposes, and to indicate what the final design of the Project may look like. The final alignment for the Project (including the design and location of associated works including bridges, culverts, stormwater management systems, soil disposal sites, signage, lighting at interchanges, landscaping, realignment of access points to local roads, and maintenance facilities), will be refined and confirmed at the detailed design stage.

A full description of the Project including its design, construction and operation is provided in *Section 4: Description of the Project* and *Section 5: Construction and Operation* of the AEE contained in Volume 1 and shown on the Drawings in Volume 3.

1.3 Purpose of this Report

Earthworks associated with construction of the Project will change catchment derived sediment loads for rivers draining to both the eastern seaboard (Mahurangi Harbour) and western seaboard (Kaipara Harbour) of the Northland Peninsula.

The purpose of this report is to inform the Marine Ecology Assessment (Bell and de Luca 2019) and the Project Water Assessment Report (Ridley et al. 2019) by means of investigating the downstream fate of fine sediments discharged by the Project to rivers which drain into the Kaipara Harbour. The fate of sediments discharged to Mahurangi Harbour is addressed in the P-Wk Water Assessment Factual Report (Fountain and Innes, 2013).

This investigation does not address sand sized sediments because sediments released from the Project construction sites are anticipated to be only fine sediments which remain in suspension after interception by stormwater control structures around construction zones[1]. We understand that routine sediment control monitoring will include monitoring of discharges from the Construction sites, with consent conditions and monitoring requirements set out in *Section 5: Construction and Operation* of the Project AEE.

The assessment of fine sediment evaluates the location and thickness of the additional sediment arising from the Project which is predicted to be deposited within the Kaipara Harbour, and where areas of elevated suspended sediments are predicted to be located within the Kaipara Harbour. The assessment address timeframes and ecological thresholds which are of specific relevance to the Marine Ecology Assessment:

- Long-term or cumulative effects of the additional sediment load discharged to the Kaipara Harbour over the expected duration of Project construction.

- Short-term assessment of large sediment loads discharged to the rivers over the days following intense rainfall events in the catchment. The key thresholds after which ecological effects may begin to occur during these short-term events are described in the Marine Ecology Assessment (Bell and de Luca 2019):

[1] The ALPURT Sediment Pond Study is referenced in the Catchment Sediment Report (Sands and Clay 2018) and summarised in Appendix A of that report, and this states that sediment retention ponds with chemical treatment result in only clay & silt being in the discharge (sand being removed), this occurs as larger particles are easier to settle, and as such only small particles generally remain in suspension. Reference to the study is Moores and Patterson (2008).

- Area of Harbour exceeding a concentration-time threshold where the suspended sediment concentration (SSC) exceed 0.08 kg/m^3 (80 g/m^3) continuously for a duration of 72 hours or more during short-term events

- Area of Harbour receiving total sediment deposition during short-term events of 1 – 3, 3 – 5, 5 – 7, 7 – 10 and >10 mm at 3 days after the event begins and at the end of the 7-days.

The effect of the Project is assessed as the *change* to these areas between the existing "baseline" situation and with the additional sediment arising from the Project.

1.4 Outline of this Report

The investigation is separated into two sections, each associated with the fate of fine sediments discharged into the Kaipara Harbour via the Hoteo River or the Oruawharo River catchments (Figure 1).

The works we performed differ between each catchment because of the information and models available, and information required to support the Marine Ecology Assessment. The agreed scope of each investigation included:

- **Hoteo River**. Literature review, coastal hydrodynamic model simulations of sediment load at the 10-year and 50-year Annual Recurrence Interval (ARI), and mapping of sediment deposition footprint and SSC in the southern Kaipara Harbour. This includes calculating the proportional increase in sedimentation rates (deposition) above the existing baseline situation attributable to the Project, and calculating the proportion of suspended solids attributable to the Project for runoff arising from extreme rainfall events in the upper catchment.

- **Oruawharo River**. Literature review, site visit and interpretative assessment including mapping of likely depositional footprint within the Oruawharo Arm of the northern Kaipara Harbour, specifically including Maeneene Creek and Te Hana Creek.

The primary output of the work we undertook is the maps of areas where the additional sediment arising from the Project is predicted to be deposited within the Kaipara Harbour, and where areas of elevated suspended sediments are predicted to be located within the Kaipara Harbour.

The structure of this report is as follows:

- Introduction and literature review describing the coastal processes within the existing environment for the wider Kaipara Harbour setting.

- Describe the methodology employed to assess the fate of fine sediment discharged to the Kaipara Harbour via the Hoteo River and Oruawharo River.

- Present and discuss results with mapped outputs provided for key ecological parameters.

- We conclude with an overall descriptive assessment of the fate of sediment discharged to the Kaipara Harbour by the Project.

- A complete library of figures and maps are appended to this report. Electronic files were also produced and are available on request.

1.5 Data provided to NIWA from the Catchment Sediment Modelling Report

This investigation relies on environmental information output from the Catchment Sediment Modelling (Sands and Clay 2019). The environmental information provided to NIWA for coastal modelling and assessment included sedigraph and hydrograph inputs for each river for particular extreme rainfall and river flow events.

Sands and Clay (2019) developed coastal sediment loads based on a statistical fit to modelled sediment loads (using data from the Pūhoi to Warkwarth project with the GLEAMS model) and Hilltop software using a Generalised Extreme Value (GEV) fit. The outputs outline the multi-day sediment loads at daily time-steps for the range of extreme storms at each ARI. Note that the ARI refers to the return interval of extreme daily sediment loads rather than the return interval of extreme rainfall intensity or river discharge.

NIWA understands that the sediment and river discharges have been calibrated against measurements at multiple locations within the catchment-sediment model (Hoteo River at Gubbs Landing, and the Waiteitei Stream at Sandersons). We also understand that annual loads have also been checked against existing Hoteo River SedNet estimates. The calibration is described in the Catchment Sediment Report (Sands and Clay 2019).

The predicted baseline sediment loads and river discharges will certainly be different (higher or lower) once the detailed design and construction method are completed. To address this, the actual sediment discharge from site during construction will be monitored and if the sediment quantum is materially different then this assessment may require review. We acknowledge that sediment load and river discharge values were provided were the best possible estimates.

The entire Project construction duration is anticipated to be approximately 7 years but the main construction phase of bulk earthworks is only proposed for 6 years. This assessment is only concerned with change to sediment loads during the bulk earthworks, and hence we refer to Project construction as the 6-year main construction period.

The additional sediment generated during Project construction relates to the efficiency of sediment control features around the construction sites, an assumed extent of open area under construction during the multi-year construction window in each catchment and rainfall/runoff relationships for various land uses. For more information refer to the Catchment Sediment Report (Sands and Clay, 2018).

Here we summarise the information which is relevant to the assessment of coastal sediment. Data was supplied in two spreadsheets; 1) short-term event loads and 2) long-term loads.

1.5.1 Short-term event loads

Tabulated sediment loads were provided for each short-term event during the multi-year construction window in each catchment. The short-term event loads were provided as the total event load over a multi-day discharge event (Table 1) as well as the day-by-day sediment load throughout the event (Table 2 to Table 5). The day-by-day timesteps required disaggregation and interpolation to sub-daily (30 minute) timesteps for coastal modelling, details of which are discussed in Section 3.2.

The data was provided at specific reporting points at the mouth each of the river and stream catchment as it flows into the Kaipara Harbour. The locations relevant to the coastal sediment modelling are the Hoteo River (Table 2), as well as the tributaries Maeneenee Creek (Table 3) and Te Hana Creek (Table 4) which drain to the Oruawharo River (Table 5). Reporting points are shown in Figure 2.

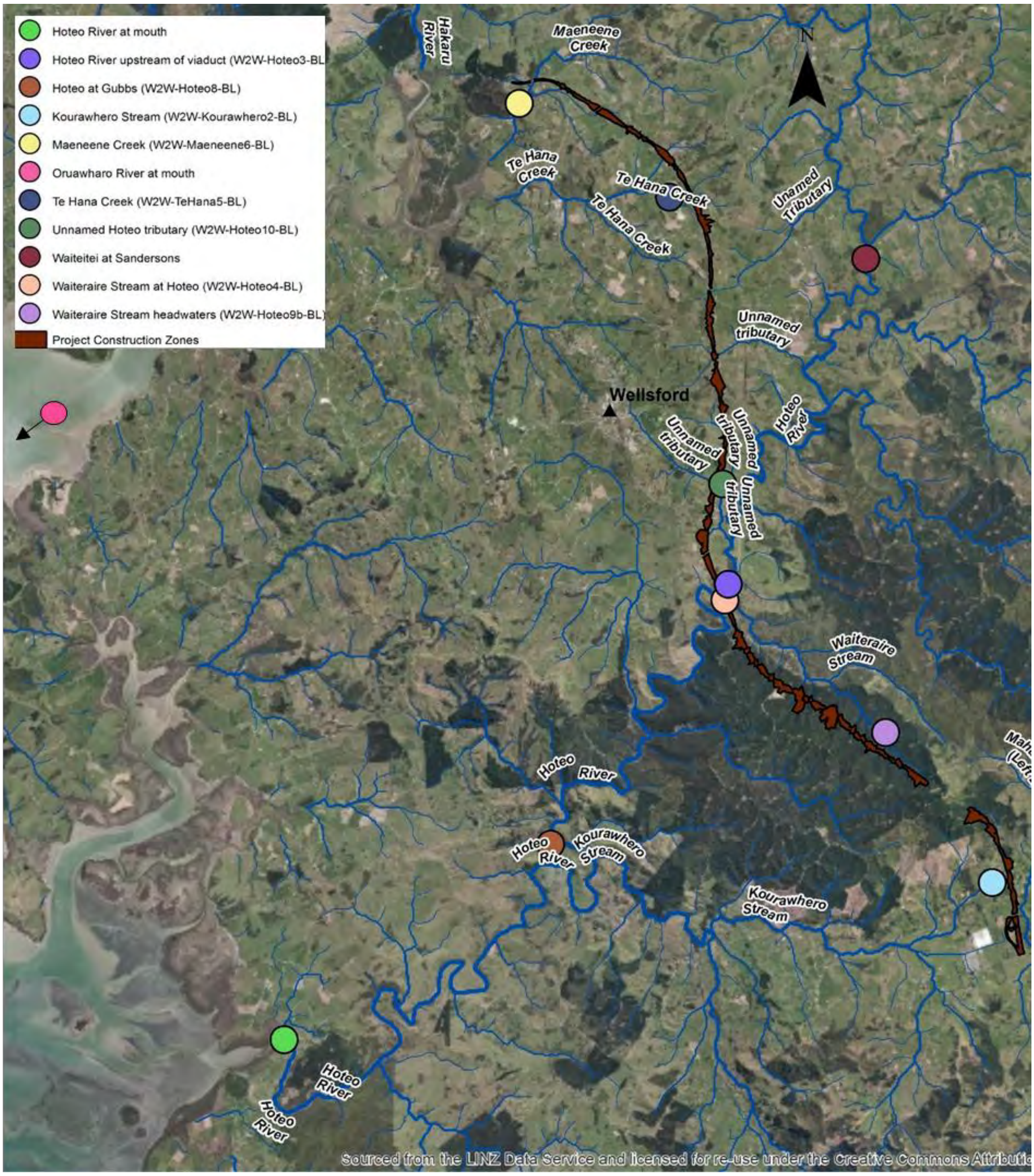

Figure 2: Catchment Sediment Model output locations as inputs to Coastal Sediment Model Sites relevant to the coastal sediment model are the Hoteo River at mouth, Maeneenee Creek, Te Hana Creek and Oruawharo River at mouth. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

We understand that short-term event sediment loads provided for the Hoteo River catchment (Table 2) relate to earthworks during summer of Year 1-2, when the largest area is under construction. Similarly, we understand that the sediment loads in the Oruawharo River and sub-catchments (Table 3 to Table 5) are also based on a worst-case assumption of earthworks area within the catchment. Refer to the Project Catchment Sediment Report

(Sands and Clay, 2018) for further interpretation of the sediment load calculations and limitations.

The provided storm-events are replicates of historic storm events which match the sediment-load at each ARI. The key parameter is the total sediment load discharged over the event, which increases with return interval. Because the storms are replicates of historic events, and, not merely scaled from one another, the differences in flow and sediment load each day are related to the sequence of each storm as it occurred.

Although Table 1 shows three ARI scenarios we have only simulated the 10-year ARI and 50-year ARI storms. The 2-year ARI event was not within the agreed scope of model simulations as the small increase to sediment load during Project construction was anticipated to have a negligible increase to sediment deposition and SSC. This exclusion was validated upon review of the 10-year ARI results which showed small downstream changes, as presented in Section 3.3.

Table 1: Total sediment loads over a multi-day discharge event for short-term scenarios in the Hoteo River and Oruawharo River. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

River system	Event	Sediment load for multi-day event			
		Baseline (t)	**Construction (t)**	**Increase (t)**	**Increase (%)**
Oruawharo River at estuary mouth	2 year ARI	1,739	1,750	11	0.65%
	10-year ARI	3,443	3,497	54	1.57%
	50-year ARI	5,301	5,465	164	3.09%
Maeneene Creek at mouth (outflow into Oruawharo River)	2 year ARI	107	111	4	3.36%
	10-year ARI	204	222	18	8.78%
	50-year ARI	325	382	57	17.71%
Te Hana Creek at mouth (confluence with Maeneene Creek)	2 year ARI	193	200	7	3.72%
	10-year ARI	356	397	41	11.49%
	50-year ARI	506	616	111	21.86%
Hoteo River at mouth	2 year ARI	5,265	5,422	157	2.98%
	10-year ARI	8,766	9,278	512	5.84%
	50-year ARI	14,866	16,759	1,893	12.74%

Table 2: Day-by-day sediment load and river discharge throughout the short-term events for the Hoteo River (at mouth). NB the multi-day event loads (Table 1) refers to the sum of quantities over days 1 – 4 below. Location shown in Figure 2. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

ARI (years)	Day 1	Day 2	Day 3	Day 4
Daily river discharge (m^3/day)				
2	3,585,102	12,083,658	8,360,013	2,946,694
10	3,494,149	16,026,688	9,485,568	2,939,520
50	3,730,383	29,436,564	18,845,806	5,801,419
Baseline event load (t/day)				
2	3,715	976	507	67
10	7,130	1,032	543	61
50	10,912	2,651	1,187	116
Construction (maximum area, year 1-2) event load (t/day)				
2	3,767	981	507	67
10	7,316	1,032	543	61
50	11,635	2,661	1,187	116

Table 3: Day-by-day sediment load and river discharge throughout the short-term events for Maeneene Creek (at mouth). Location shown in Figure 2. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

ARI (years)	Day 1	Day 2	Day 3	Day 4
Daily river discharge (m^3/day)				
2	89,490	369,750	193,838	90,756
10	193,168	801,076	159,453	-
50	248,567	1,037,207	358,913	279,291
Baseline event load (t/day)				
2	1,416	242	79	13
10	2,914	524	38	21
50	4,588	703	132	41
Construction (maximum area) event load (t/day)				
2	90	13	6.0	1.8
10	192	27	3	-
50	328	36	10	8.2

Table 4: Day-by-day sediment load and river discharge throughout the short-term events for Te Hana Creek (at mouth). Location shown in Figure 2. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

ARI (years)	Day 1	Day 2	Day 3	Day 4
Daily river discharge (m^3/day)				
2	334,117	728,807	188,228	-
10	309,216	1,264,065	256,092	148,170
50	923,941	1,420,208	446,751	156,331
Baseline event load (t/day)				
2	118	68	6.9	-
10	225	121	6.0	3.9
50	332	149	19	5.9
Construction (maximum area) event load (t/day)				
2	125	68	6.9	-
10	266	121	6.0	3.9
50	441	150	19	5.9

Table 5: Day-by-day sediment load and river discharge throughout the short-term events for the Oruawharo River (at Mouth). Location shown in Figure 2. [*Source* Catchment Sediment Report (Sands and Clay 2019)].

ARI (years)	Day 1	Day 2	Day 3	Day 4
Daily river discharge (m^3/day)				
2	963,635	7,328,662	3,854,303	1,341,345
10	3,637,891	16,057,526	3,922,495	1,853,992
50	4,646,796	21,000,180	8,002,329	3,629,753
Baseline event load (t/day)				
2	1,405	242	79	13
10	2,860	524	38	21
50	4,425	703	132	41
Construction (maximum area) event load (t/day)				
2	1,416	242	79	13
10	2,914	524	38	21
50	4,588	703	132	41

1.5.2 Long-term sediment loads

Long-term inputs used in this assessment were provided as daily timesteps of river discharge and sediment loads over the period 1974-2016 at the Hoteo River mouth and Oruawharo

River mouth. This data was used for the assessment of long-term sediment delivery to the Kaipara Harbour, which is discussed further in Section 3.2.5.

The Catchment Sediment Report (Sands and Clay 2019) provided statistics of the annual sediment loads as summarised from the long-term catchment modelling (Table 6) and the annual sediment loads predicted during the multi-year construction period (Table 7).

Table 6: Annual sediment loads statistics from long-term modelling of the Hoteo River and Oruawharo River. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

	Hoteo River mouth (t/year)	Oruawharo River mouth (t/year)
Average	25,600	9,284
Median	23,738	8,273
Minimum	10,267	2,409
Maximum	50,268	20,909
Std. Dev.	9,737	3,800

Table 7: Annual sediment loads for the multi-year construction period for the Hoteo River and Oruawharo River. [*Source*: Catchment Sediment Report (Sands and Clay 2019)].

Year	Hoteo River mouth				Oruawharo River mouth			
	Baseline sediment load (t)	**Construction**			**Baseline sediment load (t)**	**Construction**		
		Load (t)	**Increase (t)**	**Increase (%)**		**Load (t)**	**Increase (t)**	**Increase (%)**
1	25,600	25,941	341	1.3%	9,284	9,302	18	0.19%
2	25,600	25,941	341	1.3%	9,284	9,302	18	0.19%
3	25,600	25,877	277	1.1%	9,284	9,302	18	0.19%
4	25,600	25,761	161	0.6%	9,284	9,302	18	0.19%
5	25,600	25,761	161	0.6%	9,284	9,302	18	0.19%
6	25,600	25,688	88	0.3%	9,284	9,287	2	0.02%
Total	**153,600**	**154,969**	**1,369**	**0.9%**	**55,706**	**55,797**	**91**	**0.16%**
Mean annual	**25,600**	**25,828**	**228**	**0.9%**	**9,284**	**9,302**	**16**	**0.16%**

2 DESCRIPTION OF THE EXISTING ENVIRONMENT

2.1 Kaipara Harbour

The Kaipara Harbour is a complex drowned-valley/barrier-enclosed type estuary, which is located on the west coast of the Northland Peninsula (Figure 3). The harbour is one of the largest estuaries in the southern hemisphere, with a high-tide surface area of 947 km^2, of which about 43% is intertidal. The Kaipara Harbour contains a diverse range of estuarine environments, which include extensive wave exposed intertidal flats, sand barriers, extensive mangrove and salt-marsh habitats and large tidal creek systems. The harbour receives runoff from a 5,836 km^2 catchment. Landcover is predominantly pastoral agriculture, with areas of production forestry, horticulture, native forest and scrub (Swales et al. 2011).

Figure 3: **Kaipara Harbour.** Note Hargreaves Basin on Oruawharo River (circled) [*Source*: LINZ 1:500,000 series, revised 1996].

The harbour is primarily intertidal and shallow subtidal, but dissected by deeper channels; a little more than 40% of the harbour is intertidal (Heath, 1975). Haggitt et al. (2008) characterise the harbour as being "broad and shallow", with "steeply cliffed margins and low, swampy Holocene flats", although the channels are particularly deep – in excess of 70 m in some places – in the vicinity of the harbour mouth, where they delineate an extensive ebb-tide/flood-tide delta.

At Pouto Point, close to the mouth of the harbour, the neap tidal range is 1.9 m and the spring range is 2.8 m (Nichol et al. 2009); the maximum spring tidal range in the harbour is about 4.3 m (Haggitt et al. 2008). Tidal currents, particularly in the channels around the ebb-tide/flood-tide delta, can exceed 2 m/s (Green et al. 2002).

2.2 Estuary and harbour sediment transport

Estuaries receive and accumulate sediments that enter either from the ocean-side and from the land-side.

Green et al. (2017) state that for the Kaipara Harbour "Sediments that enter from the ocean-side are typically marine sands, washed in through the mouth of the estuary on a regular basis by waves and tides. Reflecting their origin, marine sands tend to accumulate in the seaward reaches of the estuary. Sediments that enter from the land-side are derived from erosion of catchment rocks and soils[2], and may comprise a wide range of grainsizes (including clays, fine silts and silts, which are collectively termed "mud" or just "fine sediments"), depending on the catchment geology, erosion processes and hydrology. Other, usually more minor, sources of sediment to the estuary include estuary shoreline erosion and in situ shell production.

Our investigation addresses the fate of sediments released from the sediment control works of the Project construction site[3]. We do not address sand sized sediments, nor their source and transport characteristics.

Within estuaries, the fate of fine sediments is governed by range of time-scales, tides, episodic events sediment plumes and waves and processes associated with baroclinic dynamics[4]. These include the large-scale estuarine circulation (which is driven by the distribution of salt, and therefore freshwater, throughout the estuary), river plumes, and lags that arise from the settling of fine particles and the consolidation of fine sediments on the bed. As a result, fine sediments tend to accumulate in characteristic parts of the estuary, which include the upper intertidal flats. Vegetation also plays an important role by baffling turbulence and wave-orbital motions, which enhances settling of fine particles and also reduces the resuspension of settled sediments (see Townsend et al. 2011).

2.3 Historical context

Although early records suggest that the Kaipara Harbour and its tributaries have long been associated with 'muddy', turbid conditions, the large-scale environmental changes documented within the Kaipara Harbour since European colonisation (i.e., deforestation, kauri-gum extraction, conversion to pastoral agriculture) have substantially increased catchment sediment loads into the Harbour (Swales et al. 2011). In many instances there have been shifts from sand to mud dominated systems, due to the increased deposition of fine terrigenous silts and clays (Swales et al. 2011). Sediment deposition was most evident in areas where both tidal and river energy are lower (upper harbour locations) (Murton, 2000). In contrast, in areas of strong tidal flow, or prone to flood events, sedimentation was minimal (e.g., 'The Funnel' and Gittos Point on the Oruawharo River).

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[2] Such sediments are called "terrigenous" when they settle on the seabed

[3] The sediments released by the Project are anticipated to be predominately fine sediments which remain in suspension after interception by stormwater control structures on the fringe of open-earthworks construction zones.

[4] Baroclinic refers to a water column that is stratified by density (i.e., freshwater is less dense than salt water)

Murton (2000) reported long-term (1852 – 1995) annual sedimentation rates (ASR) of 2.71 mm/year at Gittos Point and 16.92 mm/year 2.9 km downstream from Port Albert. These rates were comparable to similar arms of the northern Kaipara Harbour (Arapoao River; 4 to 50 mm/year, Otamatea River; 11 to 60 mm/year), and with the cored sampling of Swales et al. (2011) which is discussed further in Section 2.7. These are an order of magnitude increase in ASR relative to pre-deforestation values have been documented in the northern estuaries (e.g., Oldman and Swales 1999; Swales et al. 2005, 2007).

A classic example is the Oruawharo River and Port Albert which were once navigable by large schooners and largely mangrove free (Figure 4), but are characterized today by shallow, muddy waters and expansive swathes of mangroves extending along the shoreline towards the channel (Figure 4 and site visit notes, Appendix E).

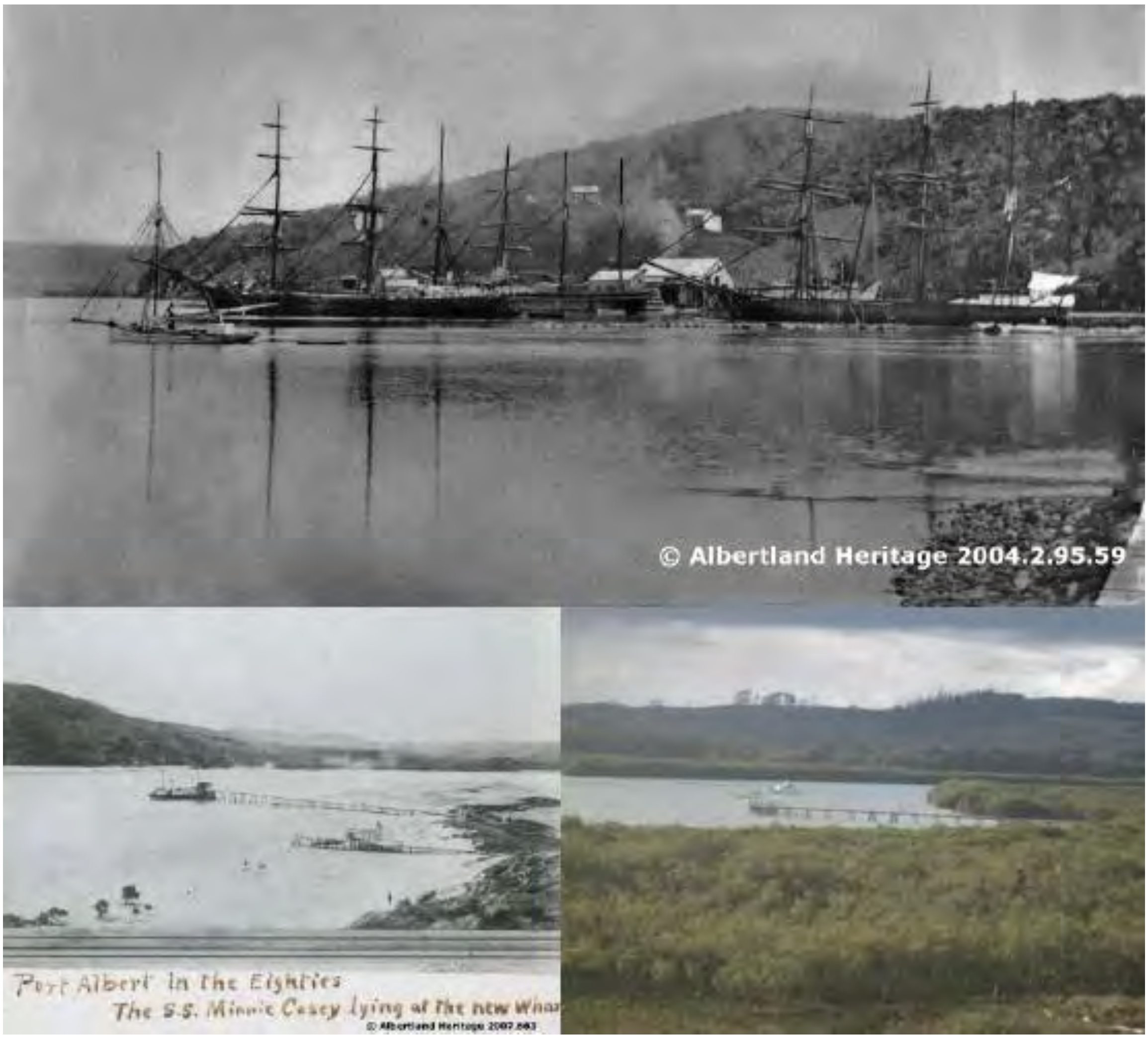

Figure 4: Port Albert wharf in a) 1855, b) circa 1880 and c) 2013 [*Source:* MPI (2014). *Credit*: a-b, Albertland Museum, Wellsford; c, M. Lowe].

2.4 Sediment Inputs

Annual catchment sediment inputs to the Kaipara Harbour are shown in Table 8 (Dymond 2016), note this excludes sediment inputs from the ocean via the harbour mouth which are primarily sand.

Dymond (2016) estimates the total sediment influx from freshwater sources to the Kaipara Harbour at 690,000 t/year, of which the Wairoa River contributes approximately 85% of the sediment. The next largest contributions are the Hoteo River (4.3%) and Kaipara River (2.7%) followed by the Oruawharo River (2.3%) and Arapaoa River (1.9%).

The catchment sediment data provided for this Project (Catchment Sediment Report, Sands and Clay 2019) show some discrepancies from the annual sediment loads as estimated by Dymond (2016). The differences are believed to be caused by improvements in model accuracy through refinements undertaken by this Project. The revised values have negligible difference to the overall Harbour sediment load, but produce a large reduction (40%) in annual Oruawharo River sediment load and moderate reduction (13%) in annual Hoteo River load. We understand the improvements made in the Catchment Sediment Report involve refining the model inputs (land uses, runoff prediction) with improved calibration to field data, hence the sediment loads used for the following assessment are those of Sands and Clay (2018) as shown in Table 8.

Table 8: Annual sediment inputs to the Kaipara Harbour from freshwater sources.

Sediment loads	Annual sediment input (Dymond 2016) (t/y)	Fraction of total input to Kaipara Harbour	Annual Sediment input (Sands and Clay 2019) (t/y)
Wairoa River	586,508	85%	-
Arapaoa River	12,900	1.9%	-
Otamatea River	7,765	1.1%	-
Whakaki River	1,028	0.1%	-
Oruawharo River	15,600	2.3%	9,284
Tauhoa River	7,512	1.1%	-
Hoteo River	29,489	4.3%	25,600
Araperera River	4,551	0.7%	-
Makarau River	5,793	0.8%	-
Kaipara/Kaukapakapa River	18,858	2.7%	-
Total	**690,004**	**-**	**-**

2.5 Sediment dispersal

Gibbs et al. (2012) and Swales et al. (2011) found clear evidence that sediment from the Wairoa River is widely dispersed to almost the entire Kaipara Harbour. Gibbs et al. (2012) commented that while "high proportions of Wairoa sediment in the main northern Kaipara were expected, the presence of Wairoa sediments … in the Arapaoa, Otamatea and Oruawharo River estuarys as well as in the southern Kaipara Harbour, shows that fine sediments from the Wairoa catchment are being widely dispersed". However, while the Wairoa River sediments dominate the overall sedimentation regime of the smaller arms in the northern sector of the Harbour, at the heads of those arms sediment is most likely to be dominated by mud derived from local sources (Figure 5).

In the central and southern sectors of the Harbour, Gibbs et al. (2012) found intertidal flats near the Hoteo River mouth are almost entirely dominated by Hoteo sediments (Figure 6), and that the dispersion pattern of sediment from the Hoteo River extends north and south across the eastern sandflats of the southern harbour (Figure 6).

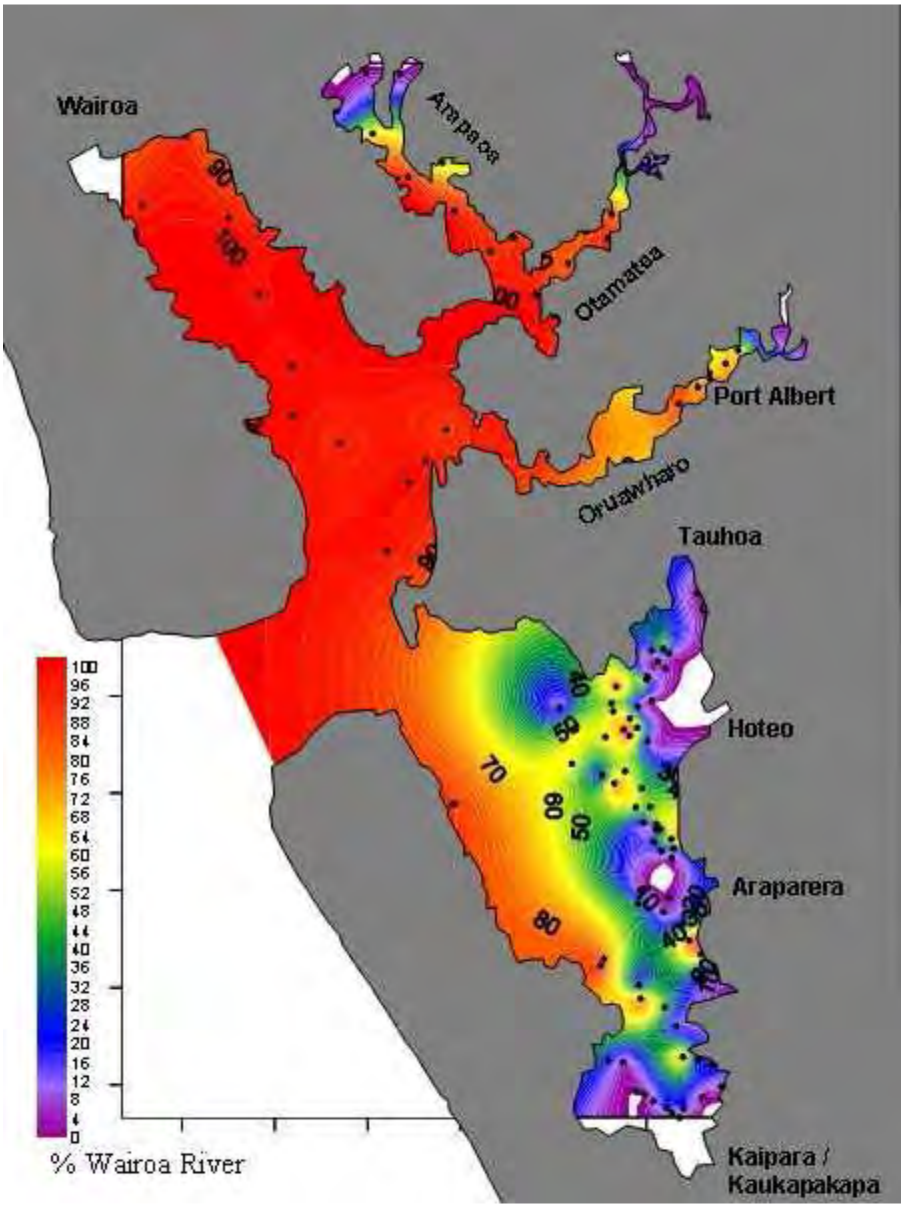

Figure 5: Deposition of sediment derived from the Wairoa River within the Kaipara Harbour. The pattern is indicative and subject to interpolation between the limited number of sample locations (solid circles). [*Source*: Gibbs et al. (2012)].

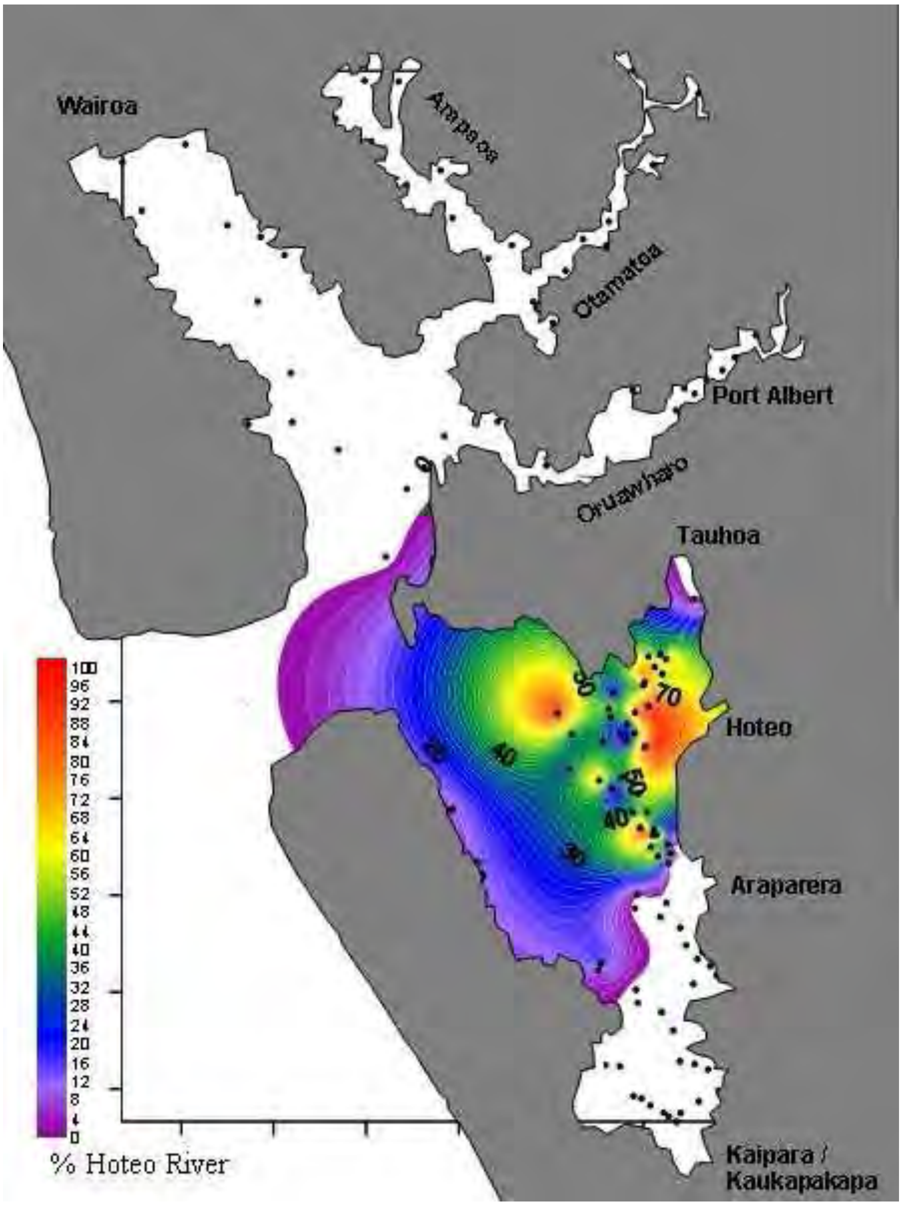

Figure 6: Dispersion of sediment derived from the Hoteo River across the Kaipara Harbour. The pattern is indicative and subject to interpolation between the limited number of sample locations (solid circles). [*Source*: Gibbs et al. (2012)].

The recent work by Reeve and Green (2016) and Green et al. (2017) modelled the distribution of sediment from all river-based sediment inputs to the Kaipara Harbour (e.g. rivers named in Table 8). The focus of their work was to establish annual sediment accumulation rates and apportion these rates to sediment sources based on extreme event-driven scenarios (1, 10 and 100- year ARI river discharges) over a 30 day model period. Their outputs show the proportional aggregation of dispersed sediment into 14 sub-estuaries (Figure 7) encompassing the entire Harbour.

Model results show sediment from the Hoteo, Wairoa, and Kaipara Rivers is dispersed into more than half of the sub-estuaries (Figure 8) while sediment from the Oruawharo, Arapaoa, Otamatea Rivers are seen to remain almost exclusively within their source estuaries (Figure 9).

During calm periods, Reeve and Green (2016) show sediment from the Hoteo River accumulating on the intertidal sandflats in SE-6 and SE-7. This sediment is typically remobilised during periods of wind-driven wave activity, which generates large bed shear stresses on the intertidal flats. The reworked sediment is redeposited in low-energy zones predominantly along the eastern shore of the southern harbour and around the mouth of the Hoteo River. Some of the sediment reworked off the intertidal flats is entrained into the main tidal channels and eventually dispersed widely around the Harbour. Reeve and Green (2016) show that the proportion of sediment lost to the coastal ocean (SE-0) is about 8%.

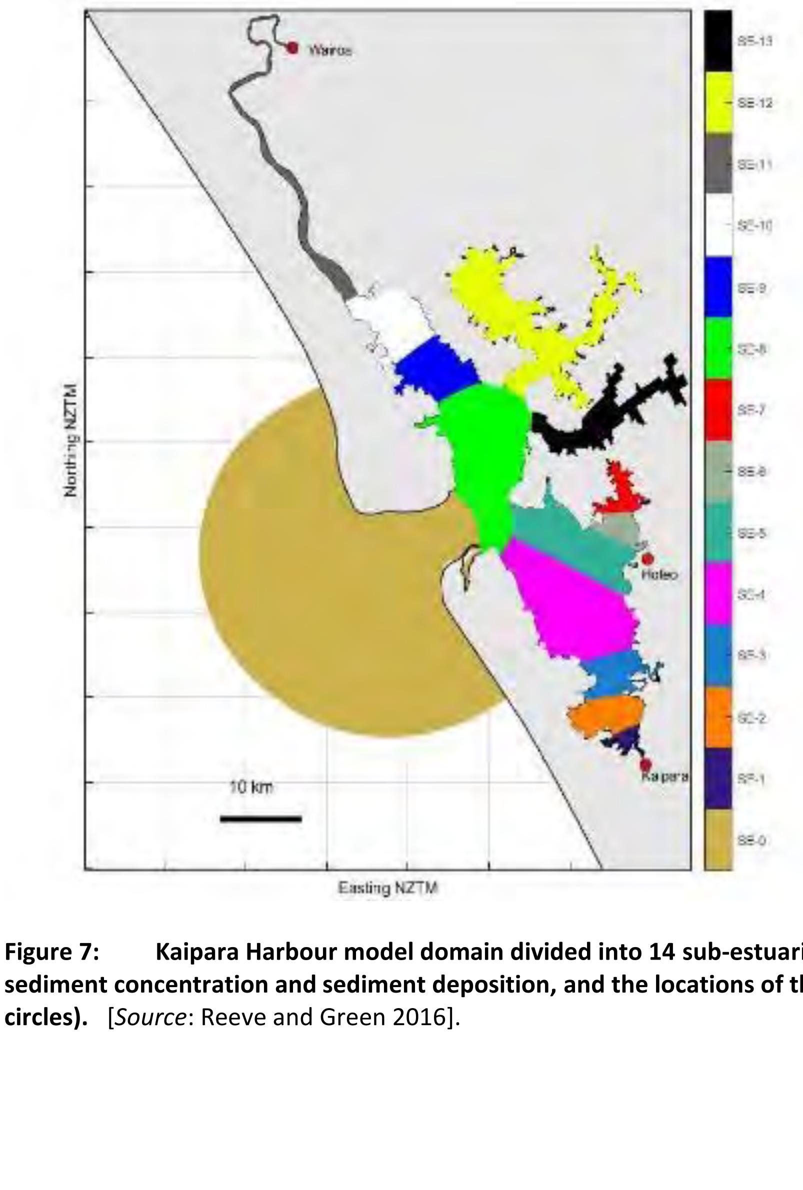

Figure 7: Kaipara Harbour model domain divided into 14 sub-estuaries used to analyse suspended-sediment concentration and sediment deposition, and the locations of the freshwater point sources (red circles). [*Source*: Reeve and Green 2016].

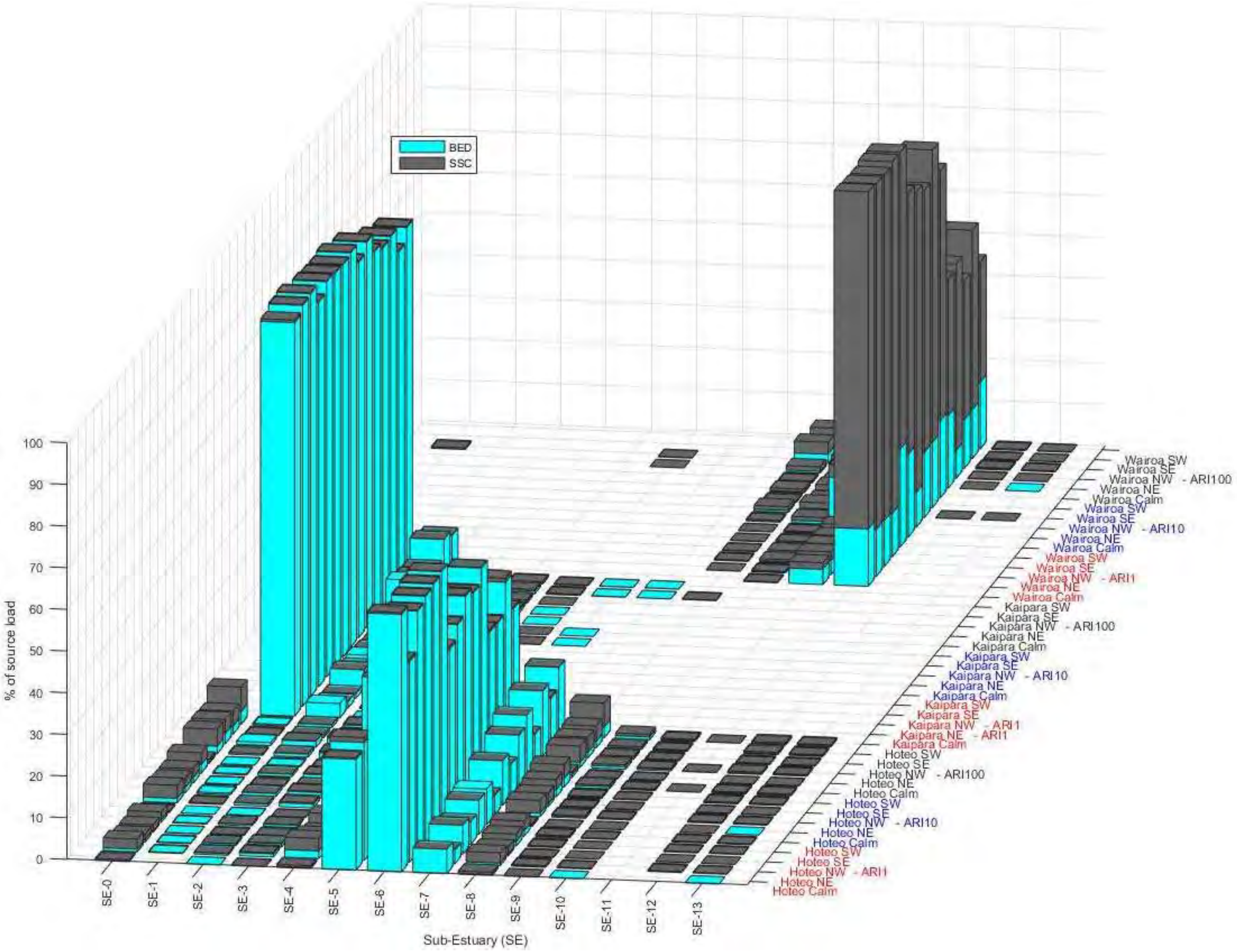

Figure 8: Percent of terrigenous sediment deposited on the bed (cyan) and still in suspension (gray) at the end of the 30-day simulation in each of the sub-estuaries for the Kaipara, Hoteo and Wairoa Rivers. The *z* axis is the percentage of the total terrigenous sediment input, the *x* axis is sub-estuary identifier, and the *y* axis is scenario (freshwater source / wind / ARI rainstorm). Percentages less than 0.01% are not shown. See Figure 7 for spatial location of sub-estuary location (SE-0 to SE-13). Wind conditions for each model run were northeast (NE), southeast (SE), southwest (SW), northwest (NW) or calm. [*Source*: Reeve and Green (2016)].

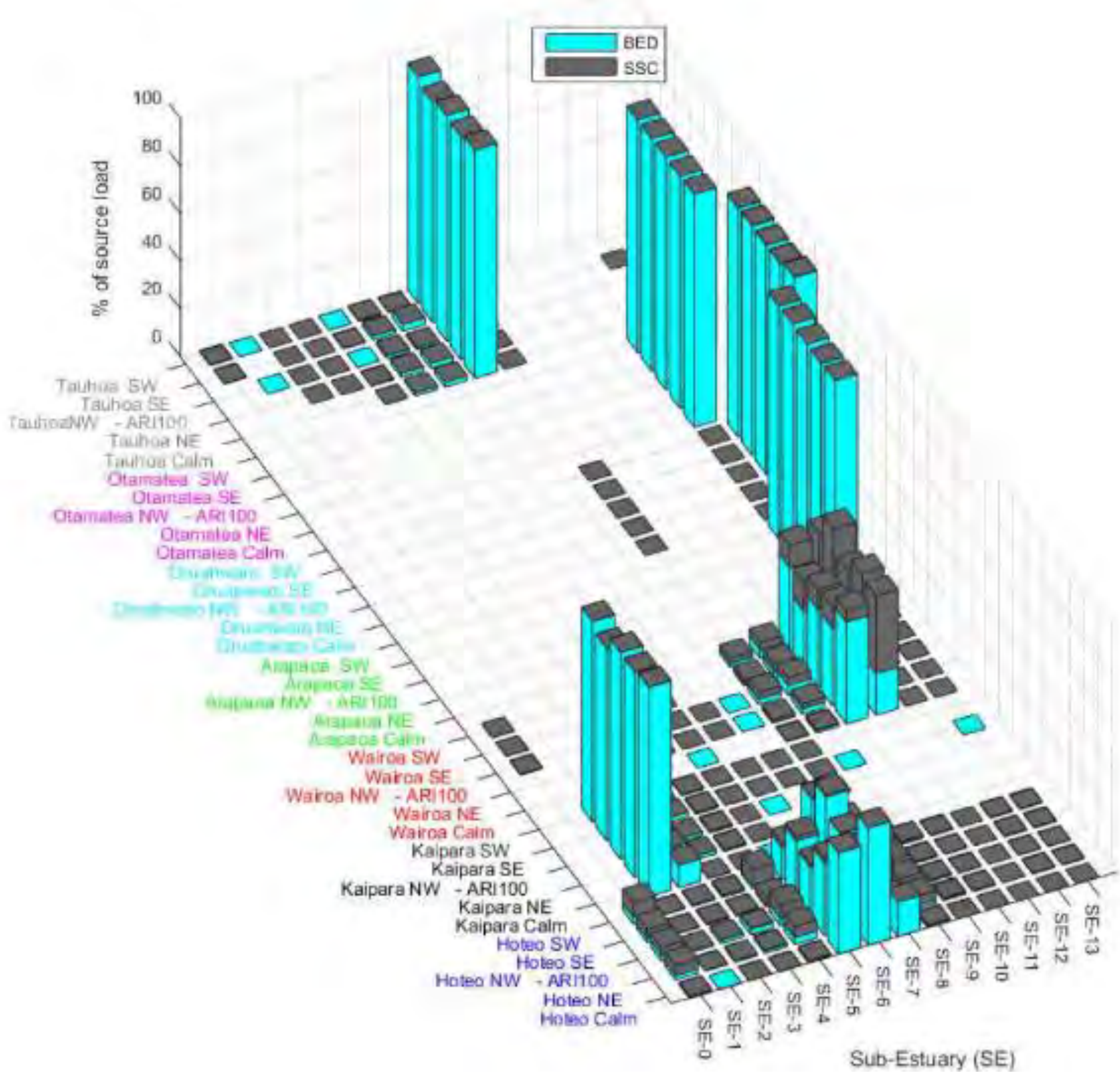

Figure 9: Catchment-mud deposition footprints for all sources and all wind directions under the simulated 100-year ARI rainfall events. See Figure 7 for spatial location of sub-estuary location (SE-0 to SE-13). The *z* axis is the percentage of the total terrigenous sediment input, the *x* axis is sub-estuary identifier, and the *y* axis is scenario (freshwater source / wind / ARI rainstorm). Percentages less than 0.01% are not shown. Wind conditions for each model run were northeast (NE), southeast (SE), southwest (SW), northwest (NW) or calm [*Source*: Green et al. (2017)].

2.6 Mud distribution

Gibbs et al. (2012) have shown that fine sediments are being preferentially deposited in the tidal rivers fringing the upper intertidal flats of the northern harbour (Oruawharo, Otamatea, Arapaoa), and in the southern Kaipara near river mouths (Tauhoa, Hoteo, Arapaera, Kaipara) (e.g. Figure 5, Figure 6).

The composition of surface sediment in these areas are shown in Figure 10 and Figure 11. In the southern Harbour, the mud content of bed sediments was found to vary from less than 2% on the lower-middle intertidal flats (e.g., Kaipara Flats, Omokoiti Flats, and the flats flanking Tapora Island) to greater than 50% on the upper intertidal flats south of Shelly Beach, Tauhoa Creek and Oruawharo River. In the more exposed areas of the southern Harbour, firm packed rippled sand predominated (Hewitt and Funnell, 2005). In the northern Harbour, sediment on the intertidal flats in the upper reaches of the smaller arms is nearly 100% mud (e.g., Oruawharo, Otamatea, Wairoa). The intertidal flats in the lower reaches which are exposed to waves consist of fine and medium sands. Samples on the edge of Hargreaves Basin show variable surface sediment composition, with samples showing 50% coarse sand, 50% medium sand or 80% mud for the three sample sites (Figure 11).

While surficial sediments within mangrove and salt-marsh habitats were not sampled in the Hewitt and Funnell (2004) survey, field observations concluded that these areas are sinks for terrigenous muds in the Kaipara Harbour (Swales et al. 2011).

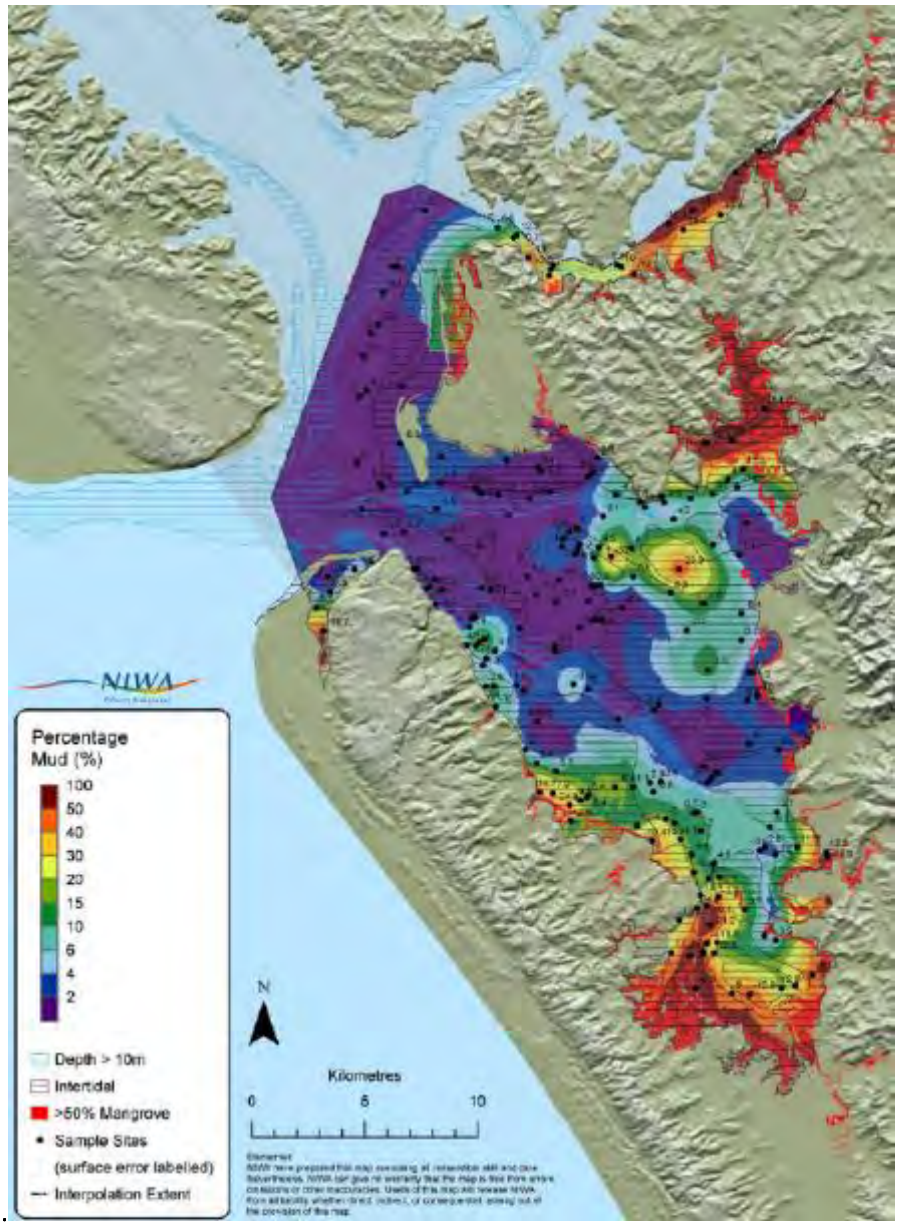

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Figure 10: Mud content (%) of surficial sediments (top 2-cm) in the southern Kaipara Harbour. Mud content is calculated as the percentage of the total sample weight. Note the boundary of Auckland and Northland lies within the Oruawharo River, and this study was only for Auckland Council. [*Credit*: Hewitt and Funnell 2004].

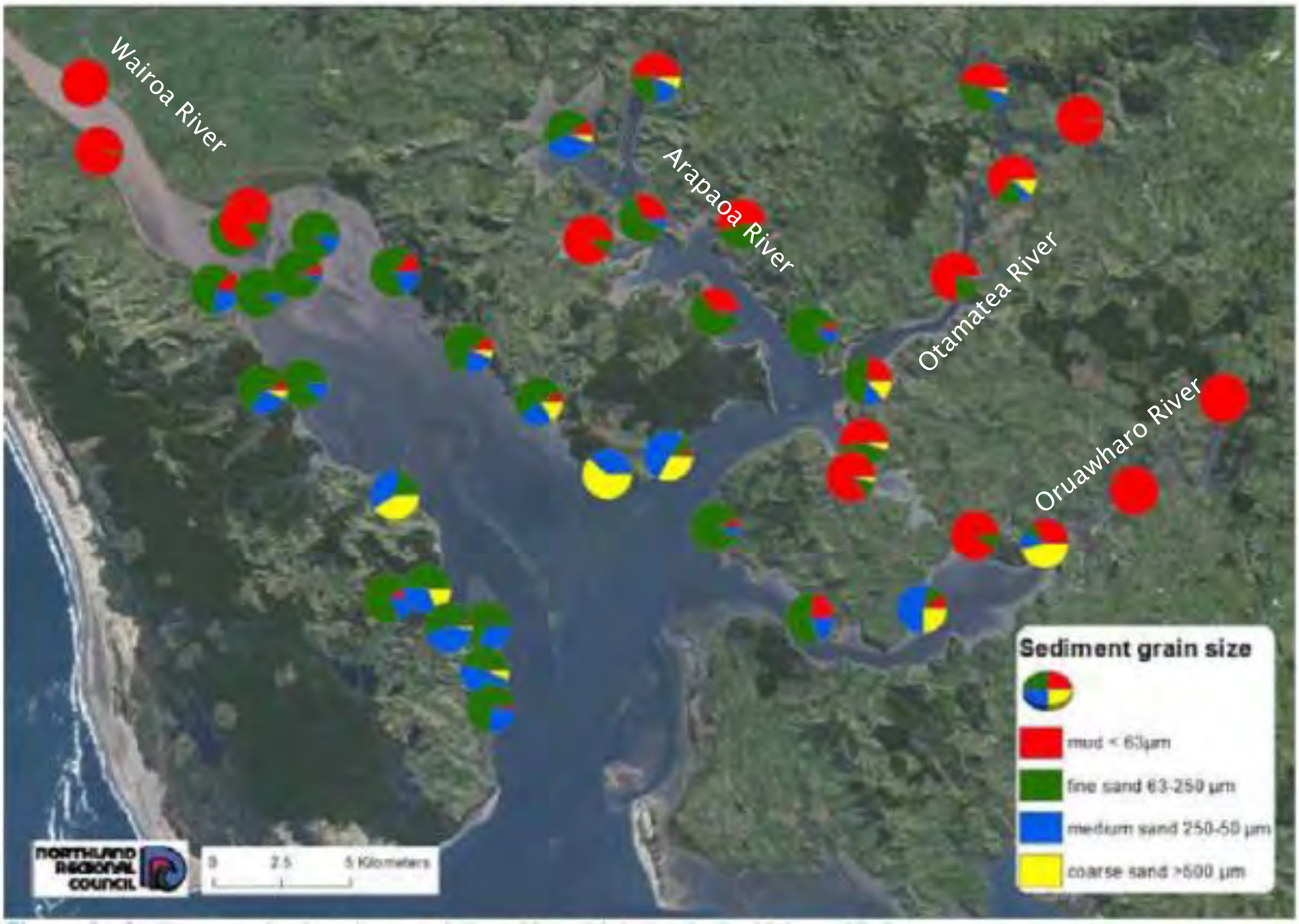

Figure 11: Sediment grain size on intertidal flats of the northern Kaipara harbour from Northland Regional Council monitoring data. [*Credit*: Griffiths 2014].

2.7 Annual sedimentation rates

Long-term sinks for fine sediments were identified by Swales et al. (2011) from sediment cores collected at 18 sites in Kaipara Harbour. The cores were analysed for fine-scale sedimentary fabric, bulk density, particle-size distribution and sedimentation rate (by radioisotopic dating). Figure 12 shows their mapped major fine-sediment accumulation zones including the southern Kaipara Harbour, Kakarai Flats in the vicinity of the Hoteo River mouth and the Arapaoa River. Other long-term mud sinks in similar environments were inferred to include the Otamatea and Oruawharo Rivers.

The measured annual sedimentation rates (ASR) from the two core sites collected near the Hoteo River mouth gave high sedimentation rates. The site closest to the mouth described as being "on the Hoteo River delta" gave very high sedimentation rates of 21 mm/year or > 19mm/year (1959-2010), depending on dating method used. Approximately 2 km west of the Hoteo mouth, sedimentation rates were 6.5 to 6.8 mm/year (1951-2010). Swales et al. (2011) also suggest that "mud will be accumulating in the mangrove forests and salt marshes that fringe the Kaipara Harbour … and most likely more rapidly than we have measured on the bare intertidal flats".

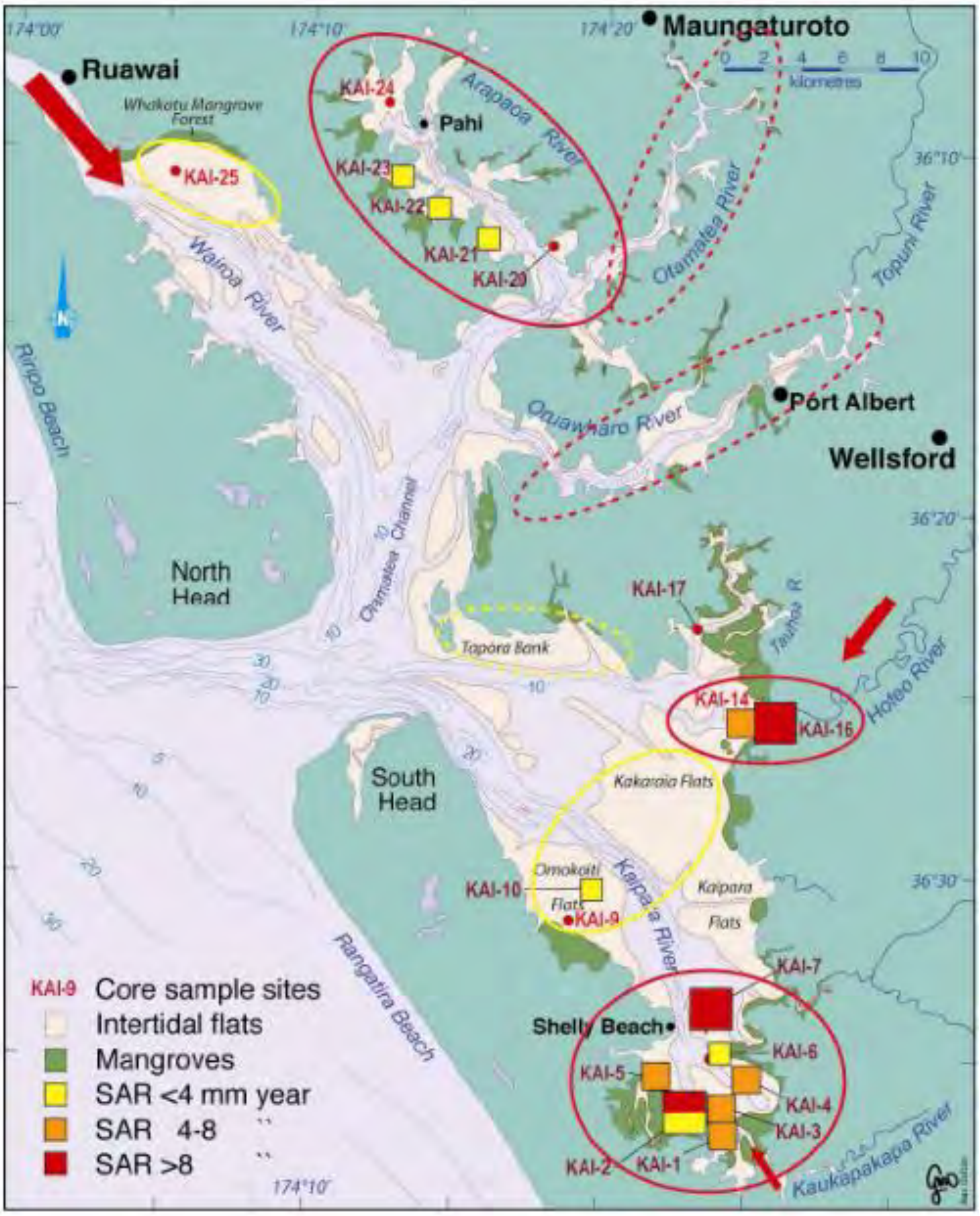

Figure 12: Summary of sediment inputs and ASR in the Kaipara Harbour (derived from dated cores) Long-term fine-sediment sinks (red ellipses) and temporary sinks (yellow ellipsis). Dotted ellipses are inferred sediment sinks. Red arrows represent the relative size of catchment sediment inputs. SAR = sediment accumulation rate = annual sedimentation rate = ASR [*Credit*: Swales et al. 2011].

Swales et al. (2011) found that most terrigenous mud is delivered to the Kaipara Harbour by episodic flood events. Cores collected within about 2 km of the mouth of the Hoteo River contained the "best examples of flood deposits, composed of pure mud layers up to 6 cm thick”. Most of these flood deposits pre-date the 1950s, and the excellent preservation of the deposits was attributed to the “close proximity to a large terrigenous sediment source and rapid post-event burial by sand”.

The recent modelling by Reeve and Green (2016) shows sediment originating from the Hoteo River during individual large episodic storms exceeds 1 mm after 15 days near the Hoteo River mouth (and within the sheltered embayments north of the Hoteo River mouth) (Figure 13) for calm winds. Reeve and Green (2016) also show that Hoteo-derived sediment from a 100 year ARI event can be transported into the northern reaches of the northern Harbour with more than 1 mm accumulating in places (Figure 14). These model estimates are consistent with the spatial pattern of long-term sedimentation derived from dated cores (Figure 12).

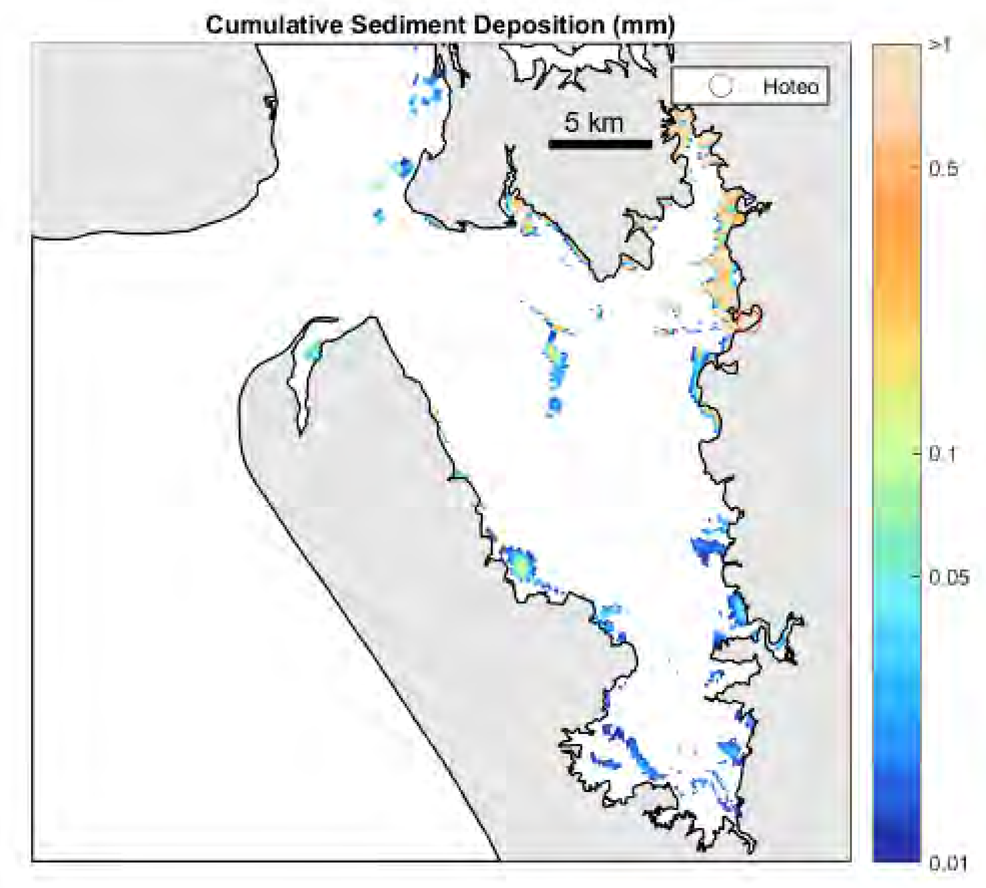

Figure 13: Sediment accumulation after 15 days of sediment (mm thickness of deposit) originating from point source Hoteo River. 10-year ARI event, calm wind, mean tide. [*Credit*: Reeve and Green (2016)].

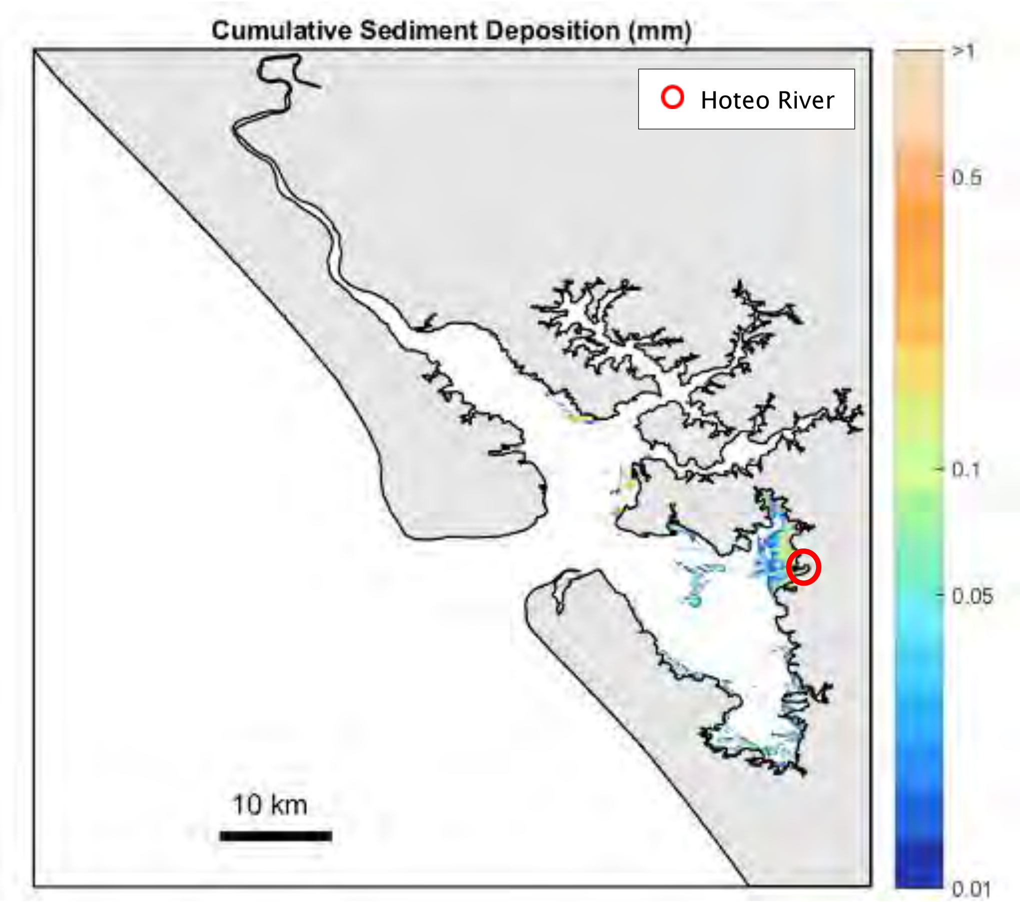

Figure 14: Accumulation after 15 days of sediment (mm thickness of deposit) originating from point source Hoteo River 100 ARI flood under a waves generated by southeasterly wind and mean tide.

Green et al. (2017) estimated the present-day sedimentation rate based on radioisotopic dating of sediment cores (Swales et al. 2011), compound specific stable isotope (CSSI) source tracing (Gibbs et al. 2012), and transport modelling Reeve and Green (2016). In making their assessment, they assumed sediment deposited at any given site arose from three sources; 1) catchment sediments, 2) shell hash that is produced in situ, and 3) marine sands washed into the harbour from the ocean by waves and tides. Green et al. (2017) interpreted the information sources to estimate present-day sedimentation rate for nine depositional environments in the Kaipara Harbour, selected for their significance to mana whenua, representative habitats, high ecological and amenity values. The sites from Green et al (2017) relevant to this Project include Site 6 (the Oruawharo River estuary) and Site 7 (the Kakarai Flats near the Hoteo River outflow), with their comments extracted below:

Oruawharo River:

- There are no measurements of sedimentation rate or suspended sediment concentrations within the Oruawharo River estuary.
- The measurable sedimentation rate is estimated as 3 mm/y based on comparison with the Arapaoa arm, where measurements are available (Swales et al. 2011). This value is the average over the whole arm, with higher deposition anticipated in

sheltered areas (e.g., mangrove forest and heads of the river/stream arms) and lower deposition in exposed reaches (e.g., Hargreaves Basin) or areas with strong currents (e.g., channels, and downstream from Hargreaves basin). However, Green et al. (2017) have "low confidence in [their] estimate" of ASR.

- 20% of sediment deposited is attributed to in situ shell production by oyster beds.
- Approximately 95% of the mud deposited in the Oruawharo arm (sub estuary SE-13 in their notation – see Figure 9) originates from the Oruawharo River catchment. About 4% originates from the Wairoa River, and trace amounts originate from Hoteo River. Note that this mud fraction excludes other fine sediments in the silt–fine sand fraction as measured by Gibbs et al. (2012).
- Overall, the ASR is attributed with 70% of the total sediment sourced from the local Oruawharo catchment with 30% from the Wairoa catchment.

Kakarai Flats (mouth of the Hoteo River)

- The present-day measurable sedimentation rate is estimated as 6.5 mm/year based on Swales et al. (2011) core samples who also report "very high confidence in estimates of sedimentation rate from both [cored] sites".
- 40% of the sediment accumulating in this area is from marine origin, as marine sands from the flood-tide delta situated in the inlet entrance to the west are accumulating on the Flats.
- Approximately 88% of the mud deposited in the Kakarai Flats/ Hoteo Mouth originates from the Hoteo River, with about 10% originating from the Tauhoa River to the north, and the remaining 2% from Wairoa River.

2.8 Summary

The Kaipara Harbour environment has long been associated with 'muddy', turbid conditions, caused by the large-scale land-use changes European colonisation (i.e., deforestation, kauri-gum extraction, conversion to pastoral agriculture) which substantially increased catchment sediment loads into the Harbour (Swales et al. 2011). This has created corresponding flow-on effects to water clarity, benthic community structure (e.g., increases in mud tolerant species), declining biodiversity, and declines in key biogenic-habitat forming species such as mangroves, seagrass, and bed-forming bivalves (see the wider reviews by Morrison et al. 2009, Swales et al. 2011). Order of magnitude increases in ASR relative to pre-deforestation values have been documented in the northern estuaries (e.g., Oldman and Swales 1999; Swales et al. 2005, 2007).

3 HOTEO RIVER INPUTS: COASTAL MODELLING

3.1 Overview

We have carried out sediment transport modelling to quantify dispersal and deposition of fine-sediments released by the Hoteo River. Sediment input loads to the model are derived from the catchment sediment modelling that provides a predictive estimate of sediment runoff (Sands and Clay, 2018).

Green et al. (2017) developed a method to convert the sediment loads predicted by SedNetNZ into annual-average sedimentation rate for the Kaipara Harbour. However, Green et al.'s model results are not directly applicable to the Project as their annual sedimentation-rate model does not resolve sedimentation that might occur at shorter, sub-annual, timescales. Our investigation uses the same model, relying on prior calibration and validation efforts (see Section 3.2), but refines the model inputs to Project-specific model scenarios.

Modelling sediment deposition within the harbour for the long-term construction scenario (i.e. 6 years of bulk earthworks) is not computationally feasible. Consequentially, this investigation employs an artificial acceleration approach for an annual sedimentation rate (modified from the NZTA East-West link in Mangere Inlet, Pritchard et al. 2016). This approach considers the sediment accumulation based on the individual modelled short-term scenarios and re-aggregates the deposition proportionally to the long-term wind climate and annual sediment load.

3.2 Model overview and methodology

Tides, tidal currents, wind-driven currents, waves and sediment transport were modelled using the Delft3D / SWAN model suites. The Kaipara Harbour model was first established in 2012 as a two-dimensional model for an investigation commissioned by Auckland Council to inform sediment-related management decisions and environmental management of the harbour. The model was developed into a calibrated three-dimensional cohesive sediment transport model with funding from Auckland Council and the NIWA Cumulative Effects research programme in 2013. The Kaipara Harbour model has been used by Pritchard et al. (2012) and Pritchard et al. (2013), and more recently by Reeve and Green (2016) and Green et al. (2017). A full description of the model including resolution, implementation and calibration in Kaipara Harbour is described by Pritchard et al. (2012) and Pritchard et al. (2013).

The model comprises three model grids (Figure 15), which cover:

- the northern Harbour (Wairoa estuary) (shown in black in Figure 15)
- the central Harbour (Tasman Sea offshore, Kaipara Harbour entrance, Oruawharo River and Arapaoa River estuaries) (shown in blue in Figure 15)
- the southern Harbour (includes Hoteo and Kaipara estuaries) (shown in red in Figure 15).

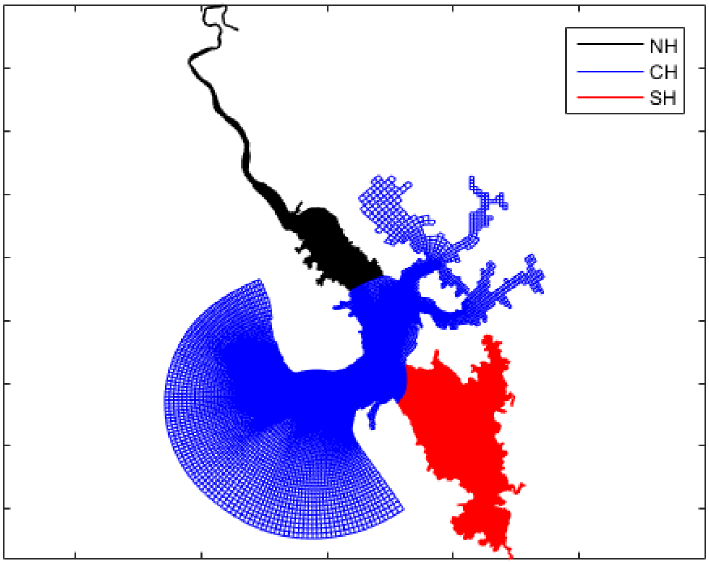

Figure 15: Model grid for the Kaipara Harbour. Northern harbour (NH) grid, central harbour (CH) grid and southern harbour (SH) grid.

3.2.1 Winds

Wind speed and direction are used in the model to generate wind-driven currents and local fetch-limited wind waves. Wave-orbital velocities in shallow water enhance bed shear stresses, which in turn are very effective at re-suspending bed sediments.

Wind speed and direction recorded at Auckland Airport AWS (1976–2016) and Dargaville EWS (2005-2016) monitoring stations were used to determine the wind climate for the simulations. Wind speed and direction are plotted on wind roses in Figure 16 and Figure 17 showing that winds are typically bi-modal, either from the southwest and northeast directions, or calm. Wind speeds less than 1 m/s are uncommon.

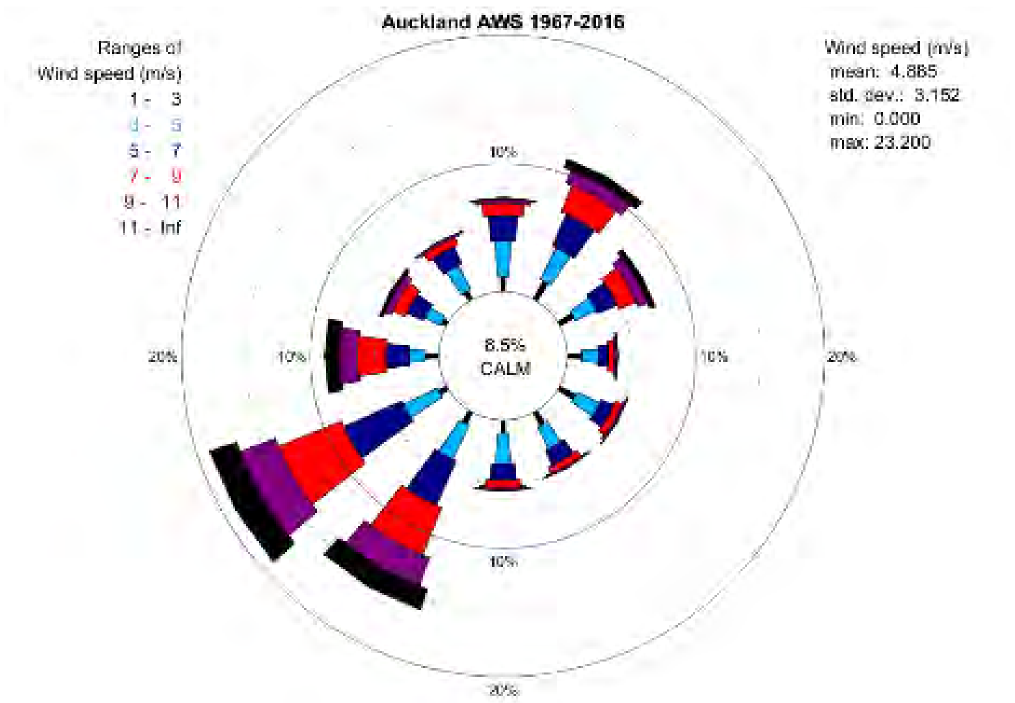

Figure 16: Auckland Airport AWS weather station wind rose, 49-year period, 1967–2016.

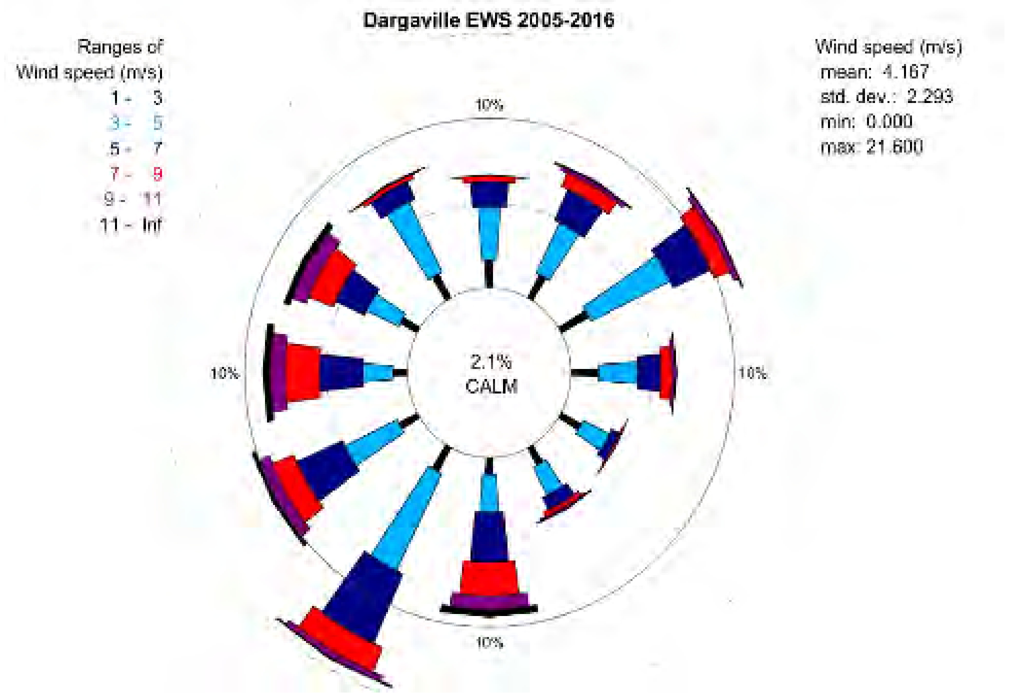

Figure 17: Dargaville EWS weather station wind rose, 11-year period, 2005–2016.

We used a simplified representative wind climate in this modelling exercise to examine the influence of wind direction on fine-sediments dispersal from the Hoteo River. Based on Figure 16 and Figure 17 we assumed a bi-directional and calm wind climate, consequently we modelled the following three wind scenarios:

- calm conditions
- southwesterly (SW) wind which is the prevailing wind in the Kaipara region, and
- northeasterly (NE) wind which generally occurs in winter and spring and brings squally weather, but is also associated with tropical cyclones that occur between December and April and bring periods of intense rain (Chappell, 2016).

Previous NIWA studies and shallow water sediment transport models developed for the Kaipara Harbour and Hauraki Gulf (Pritchard et. al., 2015) found that wind speeds below 7.5 m/s had little effect on wave generation and resulting wave-induced sediment transport. When wind speeds exceeded 7.5 m/s waves become important.

Wind speeds in the model were ramped up from zero (at t=24 hours) to 7.5 m/s (at t=48 hours – aligned with start of the river discharge), and sustained at 7.5 m/s for the remainder of the simulation. The gradual increase of wind speed was included to prevent the development of shock waves and associated inertial currents in the model domain. As per Green et al. (2017), winds stronger than 7.5 m/s were not simulated. Although stronger winds are known to generate larger waves and stimulate more sediment transport, the assumption was made that the 7.5 m/s wind speed is adequate to reproduce the wave generation process and general pattern of sediment resuspension within the model. This assumption would seem reasonable given the agreement between model predictions and measurements of sediment deposition near the mouth of the Hoteo River.

3.2.2 Freshwater and sediment inputs

The sediment transport model requires inputs of river discharge (m^3/s) and SSC (kg/m^3). However, data for coastal modelling were provided as daily values of freshwater discharge (m^3/day) and sediment load (t/day) as matched to a historic storm event for each ARI. This temporal resolution is too coarse for the hydrodynamic and sediment transport model, which used a 5-minute timestep.

Details of the method used to transform the supplied sediment and freshwater data into a form suitable for modelling is shown in Appendix A. The key aspects of the transformation were to retain the total sediment load of the multi-day event (from Table 1) while developing realistic sediment concentrations for the model. The method ensured that the freshwater inputs and sediment loads for the model (sub-daily timesteps) were the same over the duration of the event as supplied from the catchment model (daily timesteps).

A simulated particle size of 20 micron was used here to represent the fine-sediment fraction. The sand-fraction of sediment runoff is assumed to be intercepted by sediment control methods (refer to Sands and Clay 2019).

Figure 18 and Figure 19 show the timeseries of freshwater discharge and suspended sediment concentration used as inputs into the model. In the 10-year ARI event the calculated suspended sediment concentration has a double peak which is a product of the peaks in the sediment load (first peak) and flow (second peak). In the 50-year ARI scenario, the timing of peak of the sediment load and the peak of the flow differs from the 10-year ARI scenario (because of the underlying scaled reference hydrograph provided) resulting in a single SSC peak.

Note that the high background SSC prior to the 50-year ARI events (0.450 kg/m^3) is an artefact of the scaling procedure and is inconsequential as the flux of sediment is low.

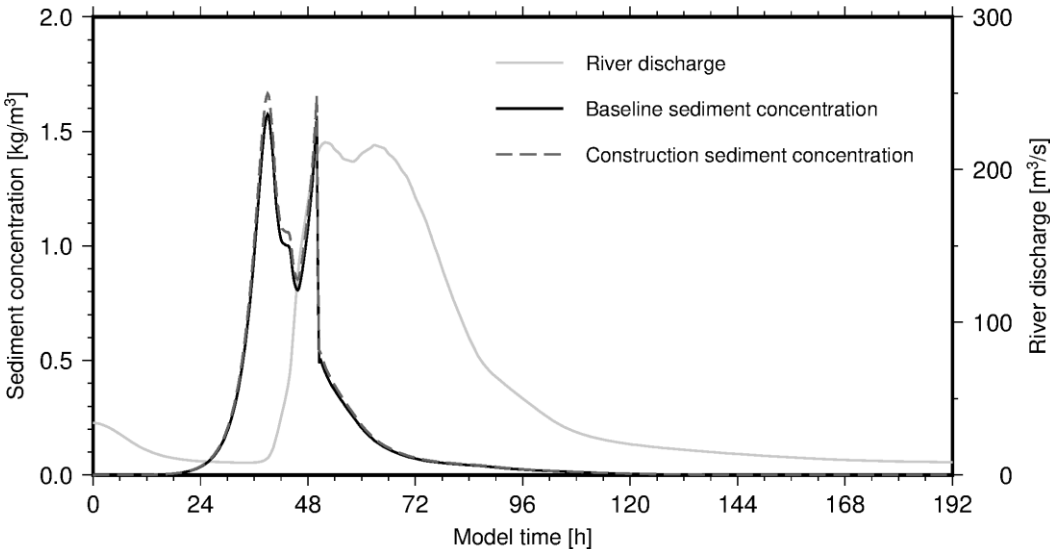

Figure 18: SSC concentration and river discharge used as input for the 10-year ARI scenarios. The black line is the SSC for the base scenario, the dashed line shows SSC for the construction scenarios. The grey line shows the river discharge.

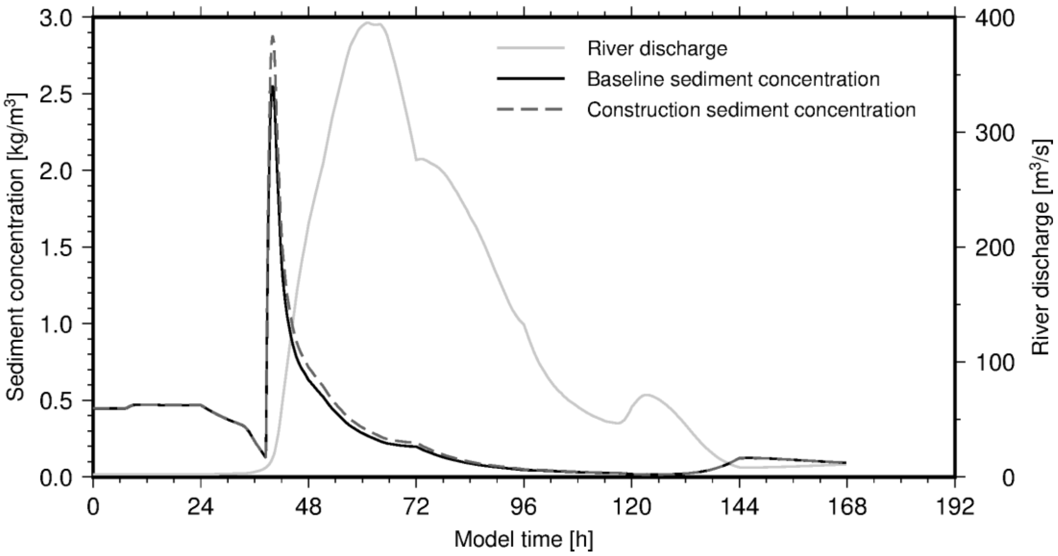

Figure 19: SSC concentration and river discharge used as input for the 50-year ARI scenarios. The black line is the SSC for the base scenario, the dashed line shows SSC for the construction scenarios. The grey line shows the river discharge.

3.2.3 Model limitations and exclusions

The Delft3D model incorporates locally generated wind-waves within the harbour, but does not include offshore swell entering the harbour mouth. The effect of ocean swell on the fine sediments discharged from Hoteo River is expected to be secondary to that of locally-generated wind-waves, because it is located far from the Harbour entrance.

We assume that the absence of freshwater inputs from other catchments has negligible effect on the dispersal and settlement of sediments from the Hoteo River. Consequently, only discharges (freshwater and sediment) from the Hoteo River were considered, which greatly simplifies the modelling.

The model was forced from a single open boundary by a mean M2 tide.

Pre-existing bed sediment was not permitted to move within the simulations. This simplifies interpretation of sediment deposition environments by only allowing mobile sediments to be those injected into the model from the Hoteo River. The limitation is that natural changes to the bed by waves and currents are not fully represented, however, natural variations would be small over the 1-week model period, and the investigation is only assessing changes relative to the baseline scenario.

A check was performed to investigate if the model conserves mass. For the 10-year ARI event during the Project construction period, the model showed that 91% of the sediment settled in the southern Kaipara with approximately 0.1% settling near the Harbour mouth and a negligible amount settled in the eastern and northern regions of the harbour. The remaining 8.9% either exited the model domain through the harbour mouth or was still in suspension at the end of the simulated period. This compares favourably with Reeve and Green (2016) who indicated that 8% of sediment from the Hoteo Source is lost out of the Harbour mouth over a longer (15 day) model timeframe. Therefore we conclude that the model is indeed conserving mass.

3.2.4 Model scenarios: short-term events

Each of the wind scenarios were simulated for a total of 7 days. Each simulation began 2-3 days prior to the rainfall event, which allowed time for the model to stabilise and winds to ramp-up, the model then continued for a period of 4-5 days after the peak of the river sediment discharge.

Table 9: Model scenarios for Hoteo River discharge. See Section 1.5 for a description of sediment loads and river discharge.

Modelling phase	Rainfall event ARI	Model duration	Wind direction	Sediment load	Number of model runs
Baseline	10	1 week	Calm, SW, NE	Median	3
	50	1 week	Calm, SW, NE	Median	3
Construction	10	1 week	Calm, SW, NE	Maximum area, year 1-2	3
	50	1 week	Calm, SW, NE	Maximum area, year 1-2	3
Long-term	-	1 year	Wind-rose	Median (baseline)	1
	-	1 year	Wind-rose	Median (construction)	1

To inform the Marine Ecology Assessment (Bell and de Luca, 2018) we produced snapshots of sediment dispersal and deposition at 1-day and 3-days after the discharged SSC begins to rise above background levels (0.010 kg/m^3). In this modelling, SSC rises above background at approximately 30 hours into the model time (Figure 18 and Figure 19). Previous modelling studies undertaken in Kaipara Harbour suggest that sediment dispersion in the aftermath of rainstorms occurs over a period of 5–10 days (Pritchard et al. 2013), hence the 1-day and 3-day windows do not show the final deposition footprint. However, at the end of simulation period (7-days) the predicted deposition values are expected to be closer to the final deposition footprints.

3.2.5 Model scenarios: simulated annual deposition

Modelling sediment dispersal behaviour within the harbour for the full 6-year term of the Project's construction programme is unachievable at the necessary temporal resolution (5 minute). Consequently, the short-term models cannot solely be used to predict the long-term sediment deposition footprint.

Here we present the method of predicting longer-term sediment deposition footprint derived from the short-term model simulations. These composite footprints were useful in understanding the long-term depositional patterns on the basis that sedimentation in the Kaipara Harbour is strongly episodic and tied to extreme rainfall and sediment discharge events (Swales et al. 2011). Section 3.3.4 (p.63) interprets and discusses the composite footprints alongside field measurements and literature.

Essentially, the composite footprints proportionally combined the deposition footprint from each short-term wind simulation according to the long-term wind climate. This annualised the storm-event deposition into a composite footprint for each of the 10-year ARI and 50-year ARI scenarios.

The sediment transport wind-speed threshold[5] (7.5 m/s) was applied to the long-term wind-roses for the Kaipara Harbour. Winds blowing from the southwest sector (135–315 °T) and northeast sector (315–135 °T) were assigned to the southwest (225 °T) and the northeast (45 °T) sectors respectively (see Figure 16 and Figure 17), with "calm conditions" prevailing the remaining time. The resulting percentage annual occurrence in the idealised case for wind-wave driven sediment transport was then:

- *Calm – 85%*
- *SW – 10%*
- *NE – 5%*

The composite footprint was then calculated as the sum of the short-term deposition footprints at the end of each short-term model run (7 days) weighted by percentage annual occurrence:

Composite footprint = (0.85 Calm Footprint) + (0.10* SW footprint) + (0.05* NE Footprint)*

Thereby creating a composite 10-year ARI footprint and composite 50-year ARI footprint.

3.3 Results and discussion: short-term event based simulations

The results figures of all short-term event based simulations are contained in the appendices to this report with only noteworthy figures copied into the text. Appendix B contains results of the baseline simulations (p. 84 – 119), Appendix C contains results of the construction phase simulations (p. 121 – 156), and Appendix D contains results of the differences between baseline and construction (p. 161 – 172).

Results are presented in the following order:

- Maximum SSC (kg/m^3) in each model cell over the whole model period.
- Maximum continuous time (hours) where SSC exceeds 0.080 kg/m^3.
- Sediment deposition (m) 3-days after the start of the event.
- Sediment deposition (m) at the end of the 7-day model simulation.

The effect of Project construction is also presented as difference maps and tables between the construction and baseline simulations for each wind direction and sediment-load ARI, and shown as figures of:

[5] Winds > 7.5m/s are necessary for wave-drive resuspension of sediments in the shallow waters of the harbour.

- Additional deposition (mm) in the construction phase at 3-days after the start of the storm event.
- Additional deposition (mm) in the construction phase at the end of the 7-day model simulation.

For visual clarity in the figures presented below, only total sediment deposition above 1 mm and suspended sediment concentration above 10 g/m^3 are shown. The difference plots of additional deposition have lower plotting threshold 0.02 mm to visually discern the distribution of additional sediment. Refer to Figure 20 for place name locations mentioned in the text.

Table 10 indexes all figure numbers for each of the results for all scenarios.

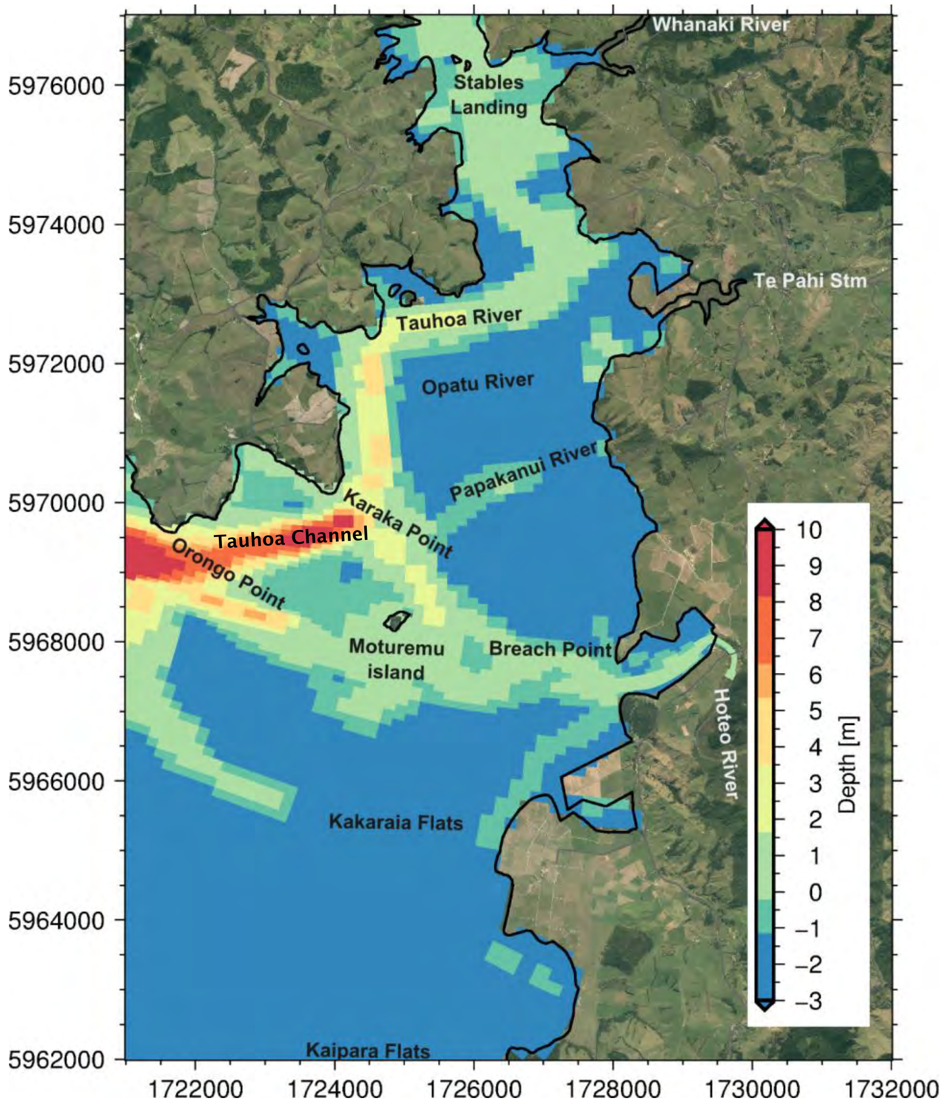

Figure 20: Model bathymetry and named features near the discharge of the Hoteo River into the Kaipara Harbour.

Table 10: Index of figures for short-term simulations.

Result	ARI/Wind	Baseline Calm	Baseline NE	Baseline SW	Construction Calm	Construction NE	Construction SW	Difference Calm	Difference NE	Difference SW
Maximum SSC (kg/m³) in each model cell over the whole model period.	10	Figure 49	Figure 38	Figure 39	Figure 73	Figure 74	Figure 75	-	-	-
	50	Figure 40	Figure 41	Figure 42	Figure 76	Figure 77	Figure 78	-	-	-
SSC (kg/m³) at 1-day after the start of the event.	10	Figure 43	Figure 44	Figure 45	Figure 79	Figure 80	Figure 81	-	-	-
	50	Figure 49	Figure 50	Figure 51	Figure 85	Figure 86	Figure 87	-	-	-
SSC (kg/m³) at 3-days after the start of the event.	10	Figure 46	Figure 47	Figure 48	Figure 82	Figure 83	Figure 84	-	-	-
	50	Figure 52	Figure 53	Figure 54	Figure 88	Figure 89	Figure 90	-	-	-
Maximum continuous time (hours) where SSC exceeds 0.080 kg/m³	10	Figure 55	Figure 56	Figure 57	Figure 91	Figure 92	Figure 93	-	-	-
	50	Figure 58	Figure 59	Figure 60	Figure 94	Figure 95	Figure 96	See Table 11		
Sediment deposition (m) 3-days after the start of the event.	10	Figure 61	Figure 62	Figure 63	Figure 97	Figure 98	Figure 99	Figure 109	Figure 110	Figure 111
	50	Figure 64	Figure 65	Figure 66	Figure 100	Figure 101	Figure 102	Figure 112	Figure 113	Figure 114
Sediment deposition (m) at the end of the 7-day model simulation.	10	Figure 67	Figure 68	Figure 69	Figure 103	Figure 104	Figure 105	Figure 115	Figure 116	Figure 117
	50	Figure 70	Figure 71	Figure 72	Figure 106	Figure 107	Figure 108	Figure 118	Figure 119	Figure 120

3.3.1 Baseline simulation

Suspended sediment

Results of the baseline simulations show that high SSC (above 0.5 kg/m^3) occurs near the mouth of the Hoteo River and extends as far as the Tauhoa Channel near Karaka Point, north of Moturemu Island (e.g. Figure 21, note these are maximum concentrations in each cell over the whole model period). In addition, concentrations above 0.05 kg/m^3 affect the entire arm of the Tauhoa River of the Harbour and as far south as the Kakarai Flats (e.g. Figure 21). The area covered by the sediment plume is smallest for the 10-year ARI calm condition and is largest for the 50-year ARI event with northeast wind conditions.

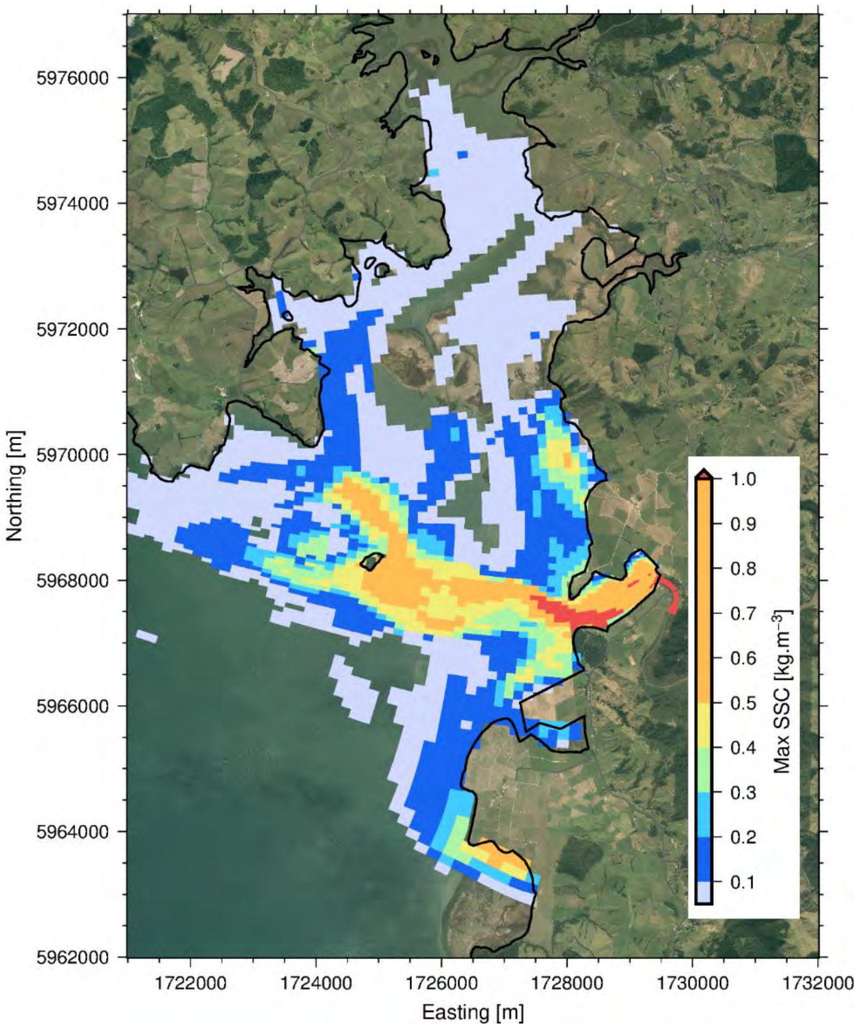

Figure 21: Maximum SSC for the base scenario of the 50-year ARI, calm wind event. Note: Sediment concentration below 0.05 kg/m^3 are not shown here.

The results also show that the sediment plume is quickly dispersed or settles on the sea bed depending on the wind and wave conditions. The SSC "snapshots" at 1-day and 3-days show the sediment-laden flow still discharging from the river mouth after 1 day, but after 3 days the highest SSCs are in the vicinity of Moturimu Island (e.g. Figure 22) and westwards toward the Tauhoa Channel.

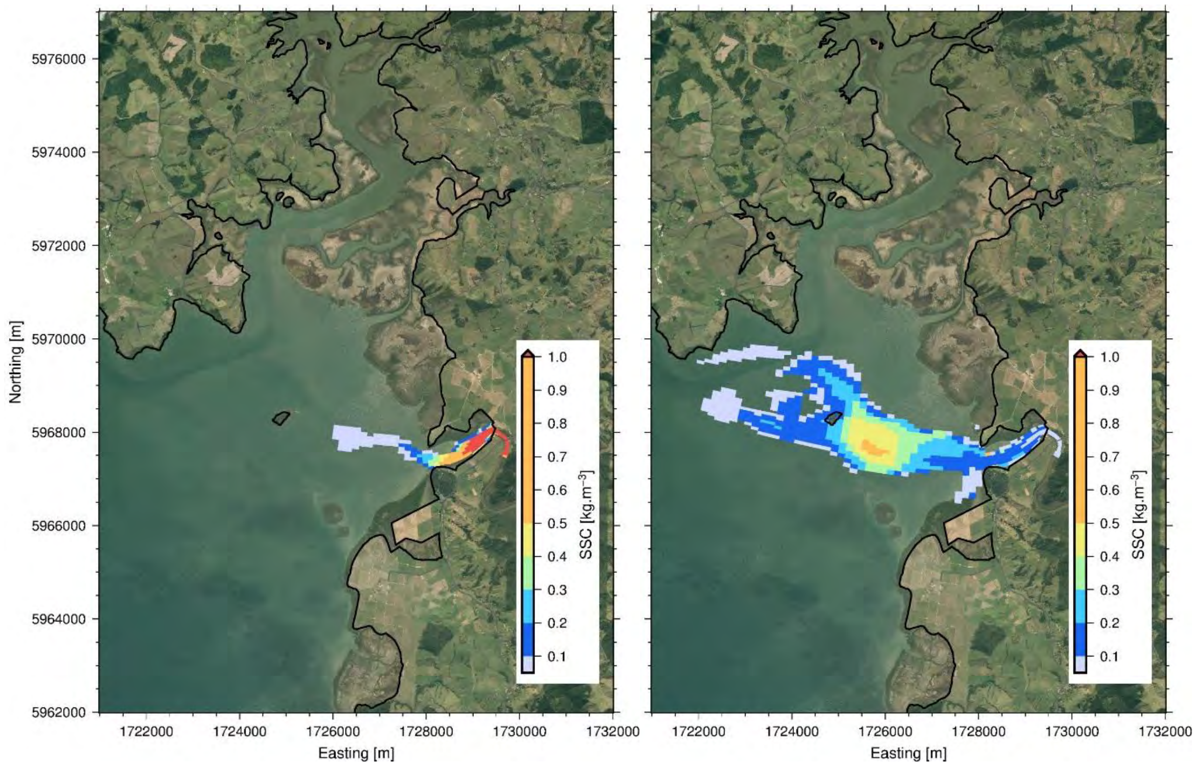

Figure 22: Sediment concentration 1 day (left) and 3-days (right) after the start of the event for the baseline 10-year ARI, calm wind event. Note the start of the event is when the sediment concentration exceeds 0.01 kg/m^3 in the model input.

The dispersal of sediment by wind-driven waves is evident as the SSC are higher and dispersed over a smaller area in the calm wind scenario compared to scenarios with winds (e.g. Figure 23). This is more pronounced 3 days after the start of the event because the wind-driven waves are delaying the settling of the sediment to the seabed.

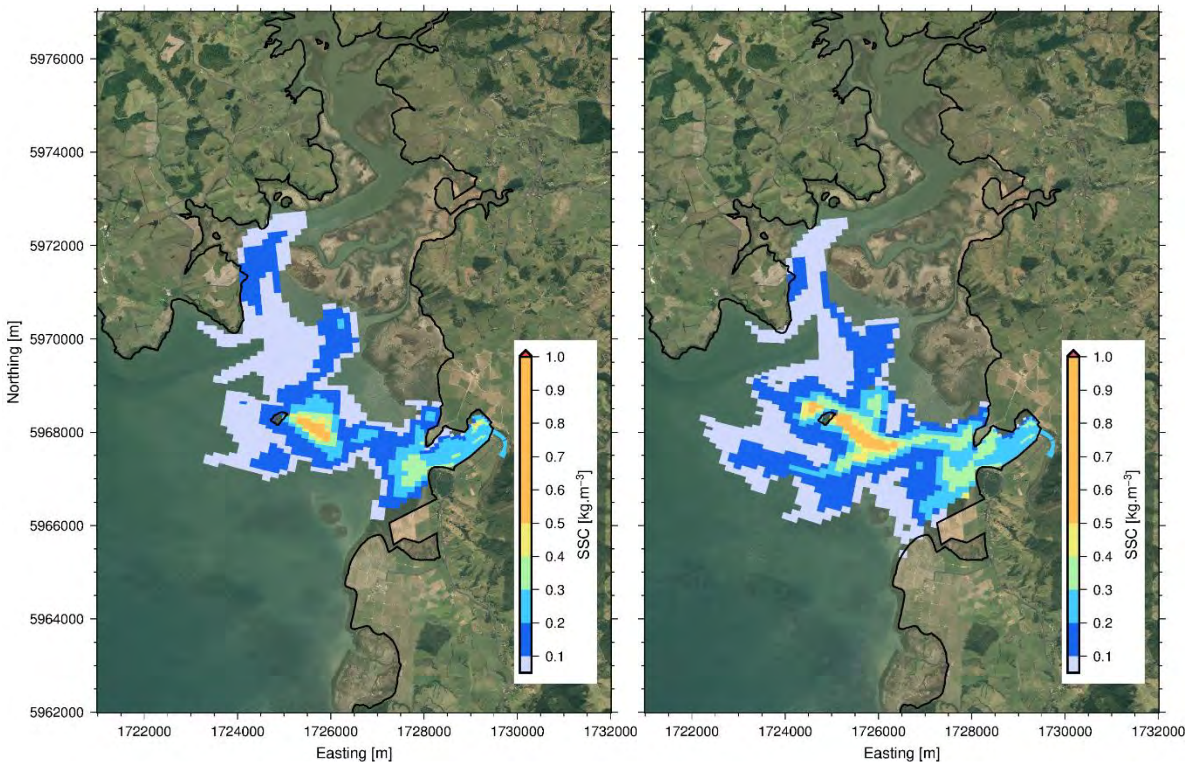

Figure 23: Sediment concentration 1 day after the start of the event for the baseline 50-year ARI, calm wind event (left) and NE wind event (right). Note the start of the event is when the sediment concentration exceeds 0.01 kg/m^3 in the model input.

The concentration-time threshold (≥ 0.08 kg/m^3 for ≥ 72 hours) is not exceeded in any of the 10-year ARI baseline simulations (see Appendix B, Figure 55 – Figure 57) or the 50-year ARI event with SE and calm winds (see Appendix B, Figure 58 and Figure 59). However, the 50-year ARI NE wind event exceeds the concentration-time threshold over an area of 2.1 ha (Figure 60). This result indicates that the NE winds and waves force sediment-laden water southwest from the Hoteo River mouth and across the upper Kakarai intertidal flats alongside the eastern shoreline with the waves preventing sediment settlement to the seabed hence leading to longer periods of high concentration. Details of this area are discussed with the results of the construction simulations (see Table 11, p. 60).

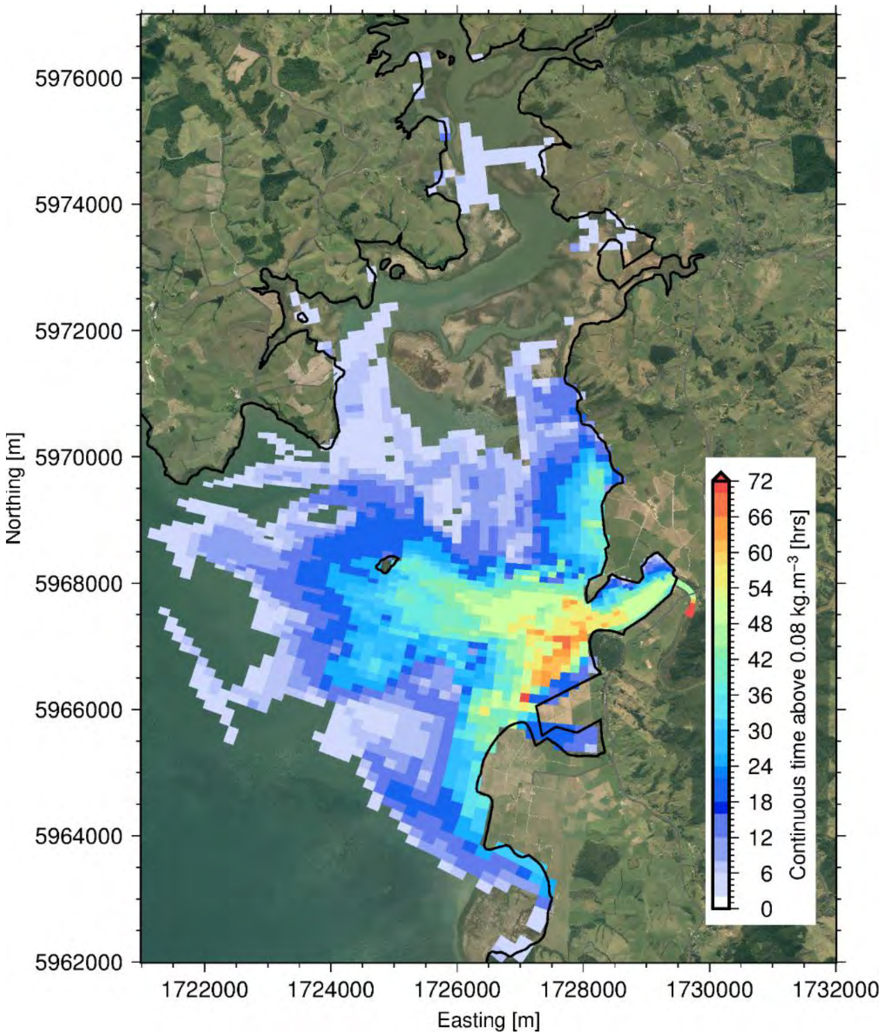

Figure 24: Maximum continuous time where the SSC exceeds 0.08 kg/m^3 for the baseline 50-year ARI, NE wind event.

Sediment deposition

Sediment deposition is calculated 3 days after the start of the event (Appendix B, Figure 61 – Figure 66) and at the end of the 7-day simulation (Appendix B, Figure 67 – Figure 72). The 7-day deposition footprints are more representative of the final deposition footprint as the discharge event has only just finished at 3-days (Appendix A, Figure 35) and a large proportion of the discharged sediment remains suspended.

Over the 7-day simulation, the greatest concentration of sediment accumulation for the 10-year ARI event is located within the river mouth (east of Breach Point) where it exceeds 10 mm in several areas (e.g. Figure 25). The sediment deposition is most localised to the river mouth in the calm scenario due to the absence of wind-waves maintaining the sediment in suspension, with only currents (tides and river discharge) dispersing the sediment away from the river mouth. The calm wind deposition footprint also spreads north into the Tauhoa River estuary, with small accumulations (1 mm m to 7 mm) in sheltered inlets and on the intertidal flats.

The pattern of deposition for the 50-year ARI event is similar, albeit with the footprint reaching further into the Harbour and up the Tauhoa River estuary with higher rates of sediment accumulation (e.g. Figure 25). The highest accumulations remain located within the river mouth where deposition exceeds 10 mm in several areas.

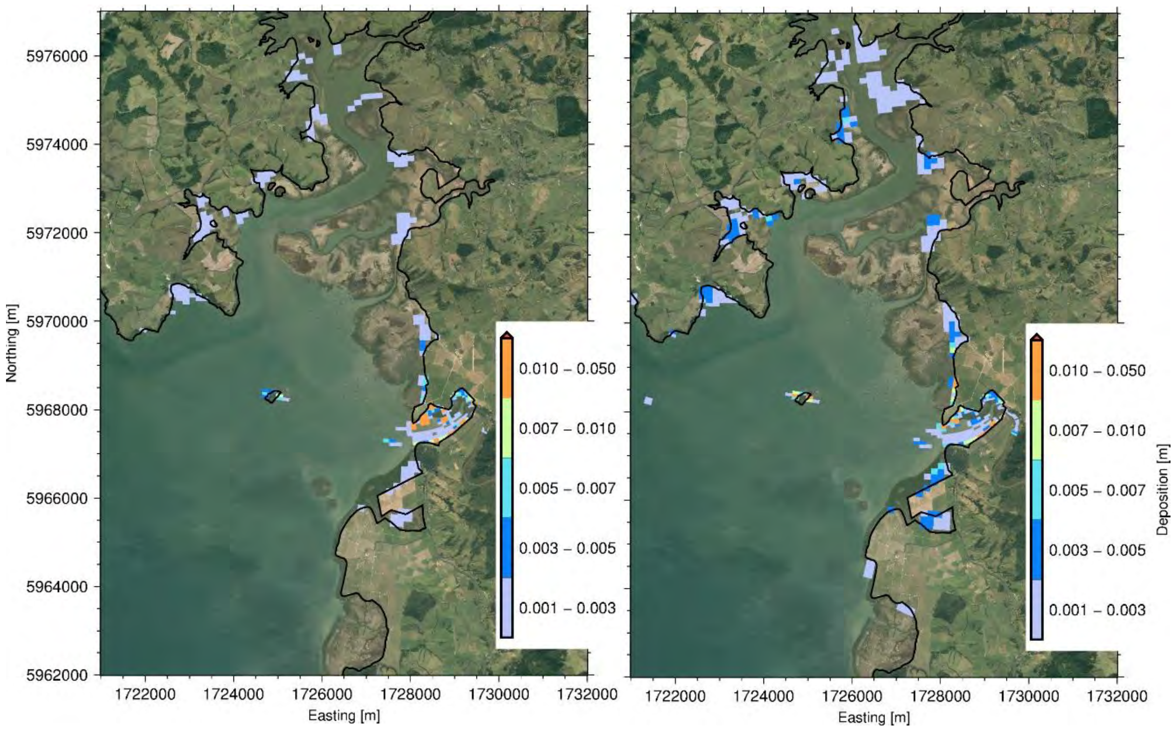

Figure 25: Sediment deposition at the end of the simulation for the baseline 10-year ARI (left) and 50-year ARI (right), SW wind events.

In summary, the model results show that plumes of sediment-laden river water are discharged to the harbour with fine sediments dispersed down the tidal channels and across the intertidal flats. Some of this fine sediment is deposited on the intertidal flats as well as transported back into tidal creeks and rivers on subsequent incoming flood tides. The model results are consistent with the spatial pattern of long-term sedimentation derived from dated cores (e.g. Figure 12) which indicated that the largest area of predominantly Hoteo-derived sediment occurs in an area between the river mouth and Moturimu Island ~3 km to the west (Swales et al. 2011). Model results show extreme storms can deposit up to 50 mm in some areas nearest to the Hoteo River mouth, consistent with Swales et al. (2011) measurement of a 60 mm deposition from a single event. The model results are also consistent with the general pattern of fine-sediment distribution within the Kaipara Harbour where during calm conditions the suspended sediments are transported landwards during the flooding tide and then settles to the bed during high-water slack, leading to the highest accumulation of sediment on the intertidal flats. During wind episodes and associated waves, the sediment is mobilised and transported further from the input source and into sheltered sedimentary environments.

3.3.2 Construction simulations

Results for the construction simulations generally show only minor differences to the baseline simulations over the measured parameters in response to the additional sediment load arising from Project construction.

Table 10 (page 52) indexes all figure numbers for each of the results for all scenarios. Appendix C contains all results figures relating to the construction simulations.

Suspended sediment

The results of maximum SSC at any point in the construction simulation show minor differences the baseline scenarios for both the 10-year ARI and 50-year ARI scenarios and for all wind conditions. The most prominent change is an increase in the area where 0.5 kg/m^3 is exceeded compared to the baseline scenarios which is generally between Breach Point and Moturimu Island (e.g. Figure 26).

Unsurprisingly the simulated SSCs after 1 day and 3 days from the start of the event are also very similar to the baseline simulation (see Appendix C, Figure 79 to Figure 90).

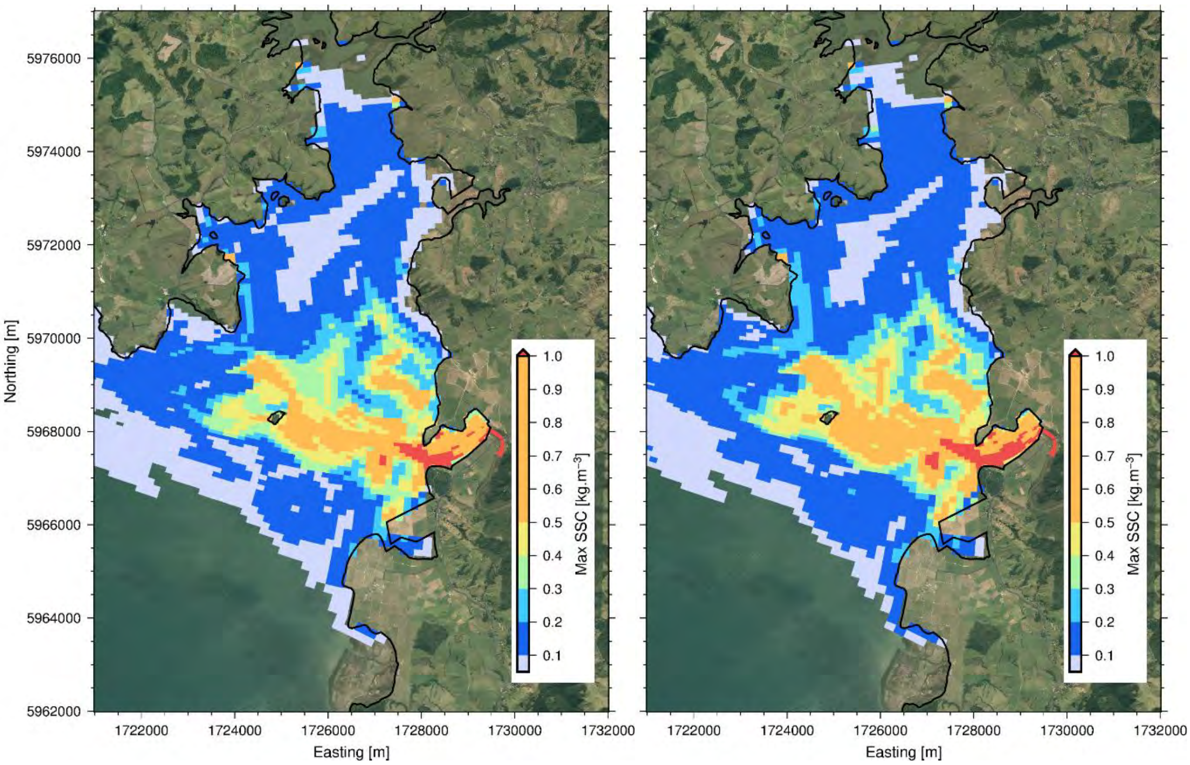

Figure 26: Maximum SSC for the baseline (left) and construction (right) simulations of the 50-year ARI, SW wind event. Note: Sediment concentration below 0.05 kg/m^3 are not shown here.

The concentration-time threshold results show similar patterns to the baseline simulation but with slightly increased values for the construction simulation. None of the 10-year ARI events exceed the threshold (Appendix C, Figure 91 to Figure 93) and neither does the calm wind 50-year ARI event (Appendix C, Figure 94).

The concentration-time threshold (≥ 0.08 kg/m³ for ≥ 72 hours) is exceeded during the 50-year ARI with SW winds construction simulation in an 3.5 ha area 1-2 km southwest of Breach Point (e.g. Figure 27), and in the 50-year ARI with NE winds construction simulation in a 1.4 ha area on the Kakarai Flats (e.g. Figure 27). Table 11 (page 60) details the areas, maximum SSC and mean SSC for the model cells exceeding this concentration-time threshold.

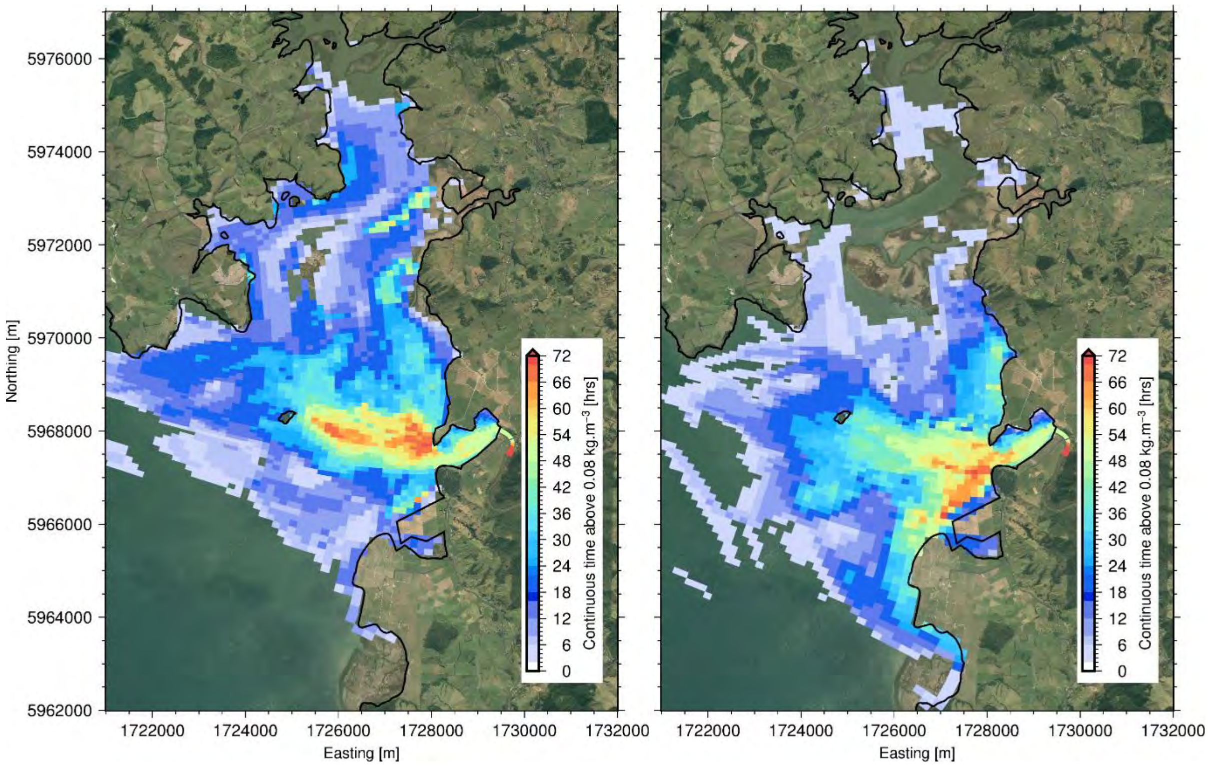

Figure 27: Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the construction 50-year ARI, SW wind event (left) and NE wind event (right). The concentration–time threshold is ≥ 0.08 kg/m³ for ≥ 72 hours.

Sediment deposition

The deposition patterns for all the construction scenarios are similar to the baseline scenarios albeit with slightly higher levels of deposition and dispersed over a slightly larger area. In the following section we see how these differences translate into sedimentation thickness.

3.3.3 Difference between construction and baseline

The short-term model results show that the additional sediment load delivered to the harbour during construction of the Project results in small increases above the baseline situation. The additional sediment increases the area of elevated SSC and areas of increased sediment deposition.

The difference between baseline and construction simulations is addressed relative to ecological thresholds, with difference figures shown with a lower plotting limit (0.02 mm) in order to maximise visual clarity.

Table 10 (page 52) indexes all figure numbers for each of the results for all scenarios. Appendix D contains all results figures for the difference between construction and baseline simulations.

Suspended sediment

Table 11 shows the total area of Harbour above the concentration-time threshold is 3.4 ha for NE winds or 1.4 ha for SW winds. The maximum duration of SSC exceeding the threshold is 75 hours under the NE wind condition in a 1.4 ha model cell near Breach Point. The mean SSC over the time when the threshold was exceeded is typically 0.2–0.3 kg/m^3 for all cells exceeded. The maximum instantaneous SSC over the time when the threshold was exceeded is typically 0.5–0.8 kg/m^3 for the NE winds but is over 1.0 kg/m^3 for the SW wind conditions.

Table 11: Area where the SSC exceeds 0.08 kg/m^3 continuously for more than 72 hours.

Scenario	Maximum continuous time above threshold (h)	Max SSC (kg/m^3)	Mean SSC for the time when SSC > 0.08 kg/m^3 (kg/m^3)	Model cell area (ha)	Easting of the cell center (m)	Northing of the cell center (m)
North East winds						
50-year ARI, NE, Baseline (Figure 24)	72.00	0.522	0.205	2.1	1727075.8	5966190.1
50-year ARI, NE, Construction (Figure 27)	72.00	0.586	0.231	2.1	1727075.8	5966190.1
	75.00	0.806	0.208	1.4	1727733.8	5967124.1
South west winds						
50-year ARI, SW, Construction (Figure 27)	72.00	1.014	0.257	0.77	1727854.7	5967703.1
	72.00	1.227	0.290	0.63	1727961.6	5967704.4

Sediment deposition

The sediment deposition results show strong similarities between the baseline and construction simulations, with small incremental increases to depositional amount and area.

The model indicates an additional sediment deposition thickness of 0.02–1 mm throughout a large proportion of the model domain at 3-days (e.g. Figure 28) and at the end of the 7-day simulation (e.g. Figure 28), with sediment dispersal strongly linked to wind conditions. A few model cells receive additional deposition above 1 mm for both the 10-year ARI and 50-year ARI events (Figure 28). None of the simulations show additional deposition above 3 mm.

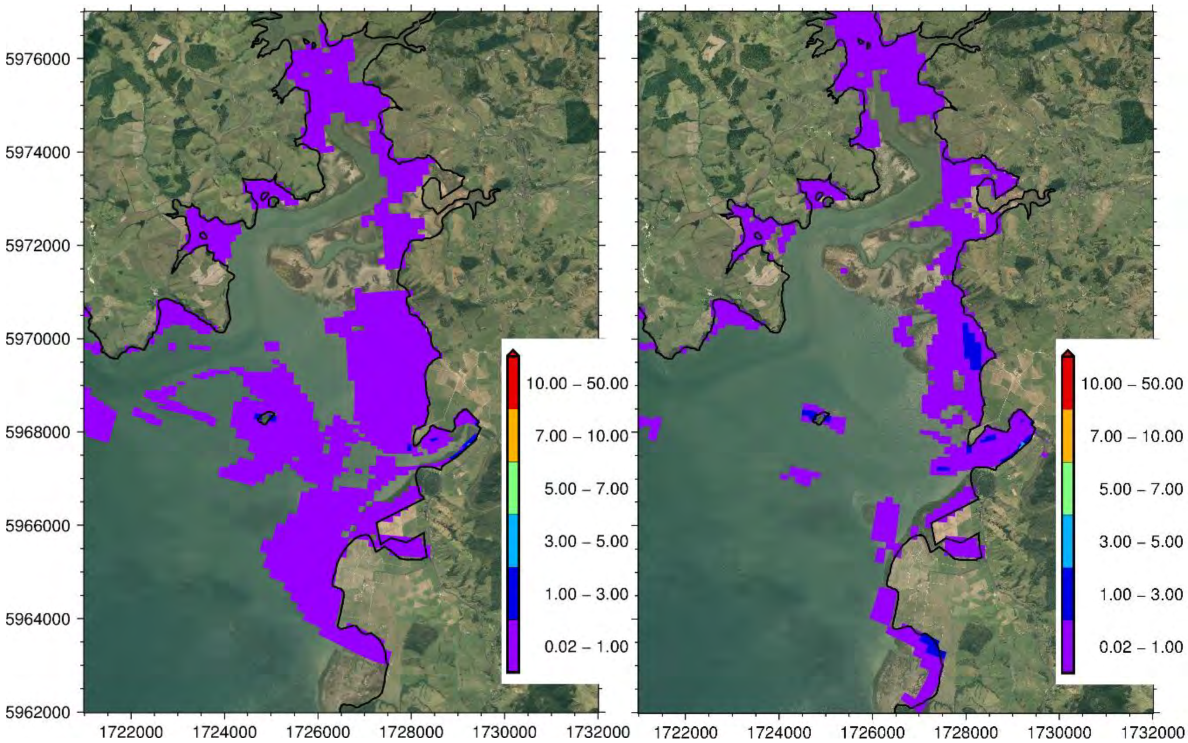

Figure 28: Additional deposition arising from Project construction at 3 days (left) and at end of 7 day simulation (right) for the 50-year ARI, calm wind event. Note: additional deposition lower than 0.02 mm are not shown here.

The area of harbour where total sediment deposition exceeds 3 mm threshold are of interest to marine ecologists. Table 12 shows that the area of harbour receiving more than 3 mm of deposition in the baseline simulations is 52–145 ha for the 10-year ARI events and 156–237 ha for the 50-year ARI events. The additional sediment arising from the Project earthworks causes a 4.4–5.5 ha increase to the area of harbour which receives over 3 mm of deposition in the 10-year ARI scenarios, or an increase of 3–10% above the baseline deposition area. Similarly, the increase to harbour area receiving over 3 mm of deposition in the 50-year ARI scenario is 11–24 ha or 6–15% above baseline.

The model cells which *only* exceed 3 mm of total deposition during Project earthworks (i.e. the model cells which comprise the 4.4–24 ha change in area) are generally on the fringe of the deposition footprints. These areas are distributed within 2 km of the Hoteo River mouth for the 10-year ARI scenarios (e.g. Figure 25) and also spreading into each of the small sheltered sub-inlets flanking the Tauhoa River inlet and the Kakarai intertidal flats in the 50-year ARI scenario (e.g. Figure 29).The baseline total deposition in these fringing areas is 2.8–2.9 mm but increase by 0.19-0.23 mm for the 10-year ARI scenarios and 0.37–0.41 mm for the 50-year ARI scenario (Table 12). The maximum additional deposition in any of the fringing model cells is 0.5 mm during the 50-year ARI SW scenario.

Appendix D contains full tables showing the change to area receiving additional deposition at the end of the 7-day simulation for multiple deposition bands between 0.02–1 mm, 1–3 mm, 3–5 mm, 5–7 mm, 7–10 mm and >10 mm.

Table 12: Change to area with sediment deposition > 3 mm, and changes to deposition within to model cells which only exceed 3 mm total deposition during Project construction

Scenario	Area with total deposition above 3 mm			Deposition in model cells which only have >3 mm deposition during Project earthworks simulations			Number of cells
	Baseline (ha)	Construction (ha)	Change (ha)	Baseline average (mm)	Average additional (mm)	Maximum additional in any cell (mm)	
10y ARI Calm	145.3	150.8	5.5	2.9	0.19	0.31	7
10y ARI SW	52.8	58.0	5.2	2.84	0.23	0.36	6
10y ARI NE	137.8	142.1	4.4	2.86	0.19	0.28	4
50y ARI Calm	237.0	255.0	18.0	2.81	0.37	0.41	14
50y ARI SW	156.1	179.9	23.8	2.82	0.37	0.43	17
50y ARI NE	178.9	190.0	11.2	2.82	0.41	0.5	14

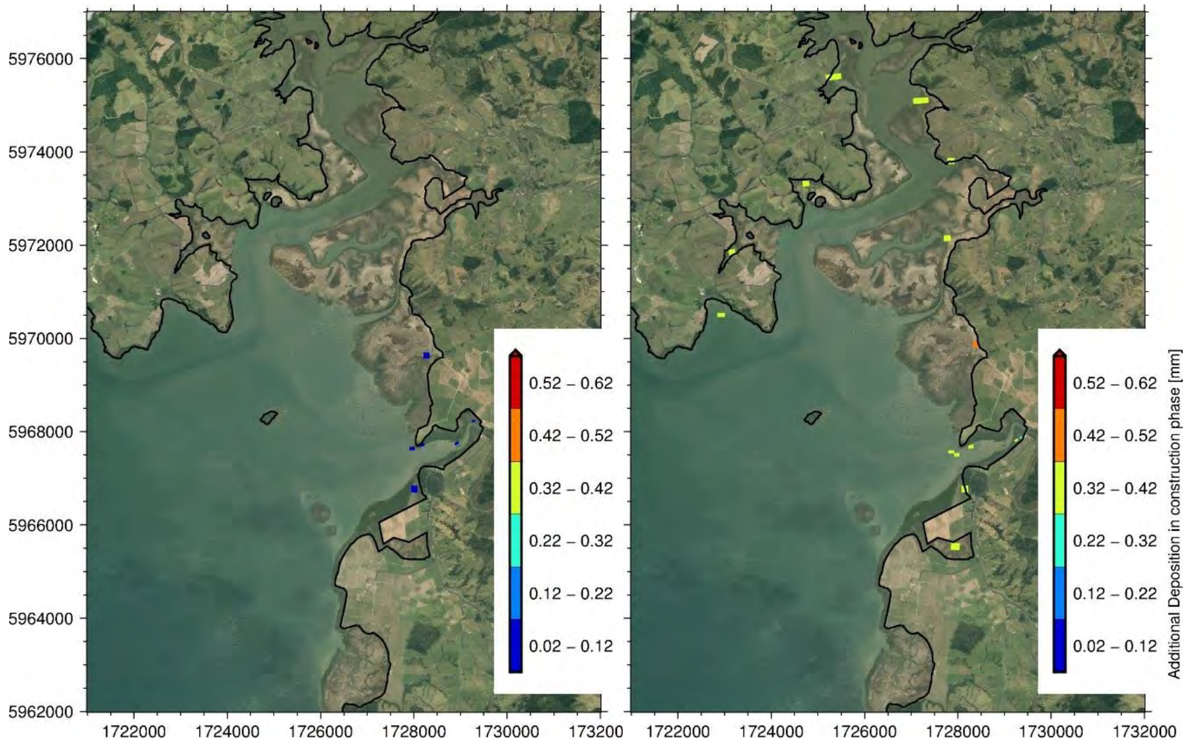

Figure 29: Additional deposition for model cells where the total deposition arising from Project construction exceeds 3 mm threshold when it was below the threshold for baseline results for the 10-year ARI (left) and 50-year ARI (right) SW wind events.

In summary, the short-term model results show that the additional sediment load delivered to the harbour during construction of the Project results in small increases above the baseline situation. The additional sediment load increases the area where the concentration-time threshold is exceeded by 1.4 ha for the SW and NE wind 50-year ARI events, all other events do not exceed this threshold. The additional sediment load settling to the seabed also increases the areas receiving more than 3 mm deposition threshold by 3-10% for the 10-year ARI events and 6-15 % for the 50-year ARI events.

3.3.4 Results and discussion: simulated annual deposition

The deposition footprints arising from the simulated annual deposition scenario (refer to method in Section 3.2.5) are interpreted alongside field measurements and other literature for the long-term sediment deposition footprint in Section 3.4. The simulated annual deposition footprints are shown in Figure 30 for the 10-year ARI and Figure 31 for the 50-year ARI events.

The annual deposition simulation results show sediment deposition is most prominent in the upper intertidal flats and sub-inlets flanking the eastern shoreline within 3 km of the Hoteo River Mouth, the tidal flats near Papakanui River and near Moturimu island. The predicted deposition exceeds 10 mm east of Breach Point for the 10-year ARI event but not for the 50-year ARI event which indicates additional flushing of this area by the larger river discharges. The largest areas of deposition outside of Breach Point have deposition of 3 – 5 mm on the intertidal flats and sheltered inlets for the 10-year ARI event (Figure 30) and 5-7 mm for the 50-year ARI event (Figure 31). For both ARI events the deposition above 0.02 mm is spread throughout large areas including the upper reaches of the sheltered inlets fringing the Tauhoa River estuary and eastern shoreline of Kakarai Flats.

The simulated annual sediment deposition patterns derived in this study are a simplification of the true annualised deposition footprints because previous modelling has shown that sediment dispersal from the Hoteo River takes place over weeks to months with dependence on wind conditions, and reworking of deposited sediments by waves and tides (Pritchard et al. 2013, Reeve and Green 2016, Green et al, 2017). Here, the 7-day model period only captures the beginning of this dispersal and hence shows greater localised deposition near the discharge point, reflecting that sedimentation within each year is strongly episodic and tied to large rainfall events.

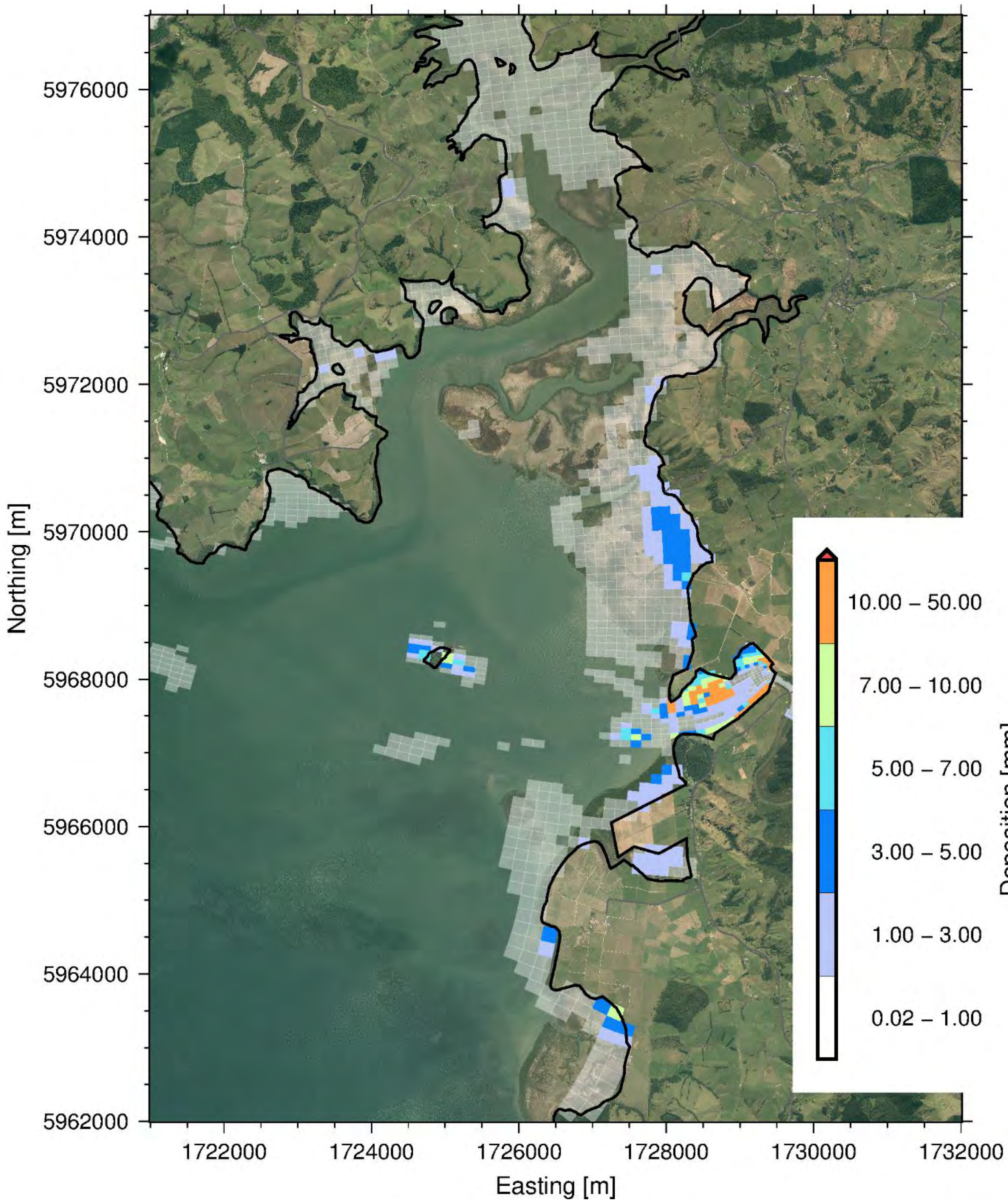

Figure 30: Simulated annual sediment deposition depth for 10-year ARI baseline scenario. Note: Deposition of less than 0.02 mm is not shown here.

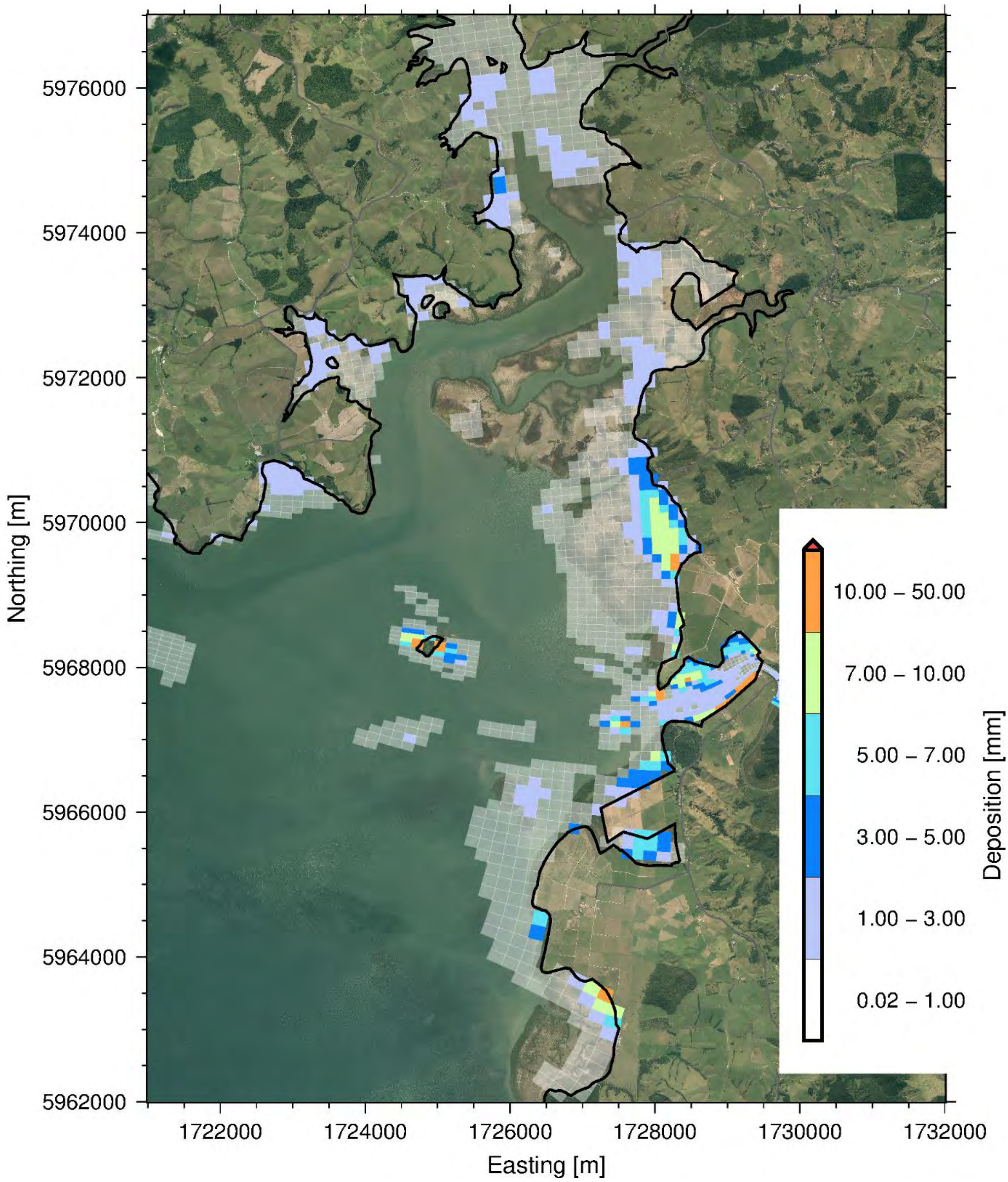

Figure 31: Simulated annual sediment deposition depth for 50-year ARI baseline scenario. Note: Deposition of less than 0.02 mm is not shown here.

3.4 Summary

Short-term

The results of the short-term modelling show that plumes of sediment-laden river water are discharged to the harbour and disperse fine sediment down the tidal channels and across the intertidal flats. Some of this fine sediment is deposited on the Harbour's intertidal flats (vegetated and unvegetated) as well as transported back into tidal creeks and rivers on subsequent incoming flood tides. The model results are consistent with the spatial pattern of long-term sedimentation derived from dated cores, previous modelling and present-day depositional environments. Overall, the additional sediment discharged by Project construction results in small increases to the SSC and depositional footprint above the baseline scenarios.

The sediment plumes for all simulations are quickly dispersed or settle to the sea bed, at a rate dependent on the wind and wave conditions, with a small (8%) proportion of sediment leaving the Harbour mouth on the ebb tide and lost offshore. At 1 day after the event begins the sediment-laden flow is still discharging from the river mouth with highest SSCs upstream of Breach Point, while at 3 days after the event begins the highest SSC levels are within the region immediately downstream of the Hoteo River mouth and near Moturimu Island. The additional sediment discharged by the Project construction results in a small overall increase to SSC, with a 1.4 ha increase to area of SSC above the concentration-time threshold in the NE and SW 50-year ARI simulations. No other simulated events exceed this threshold.

The Hoteo River sediment generally settles to the seabed in areas to the northwest of the Hoteo River mouth towards the Tauhoa River estuary, with some sediment settling on the Kakarai Flats to the south. The additional sediment discharged by the Project construction leads to an overall increase to sediment accumulation in these areas. Overall, the area of harbour receiving more than 3 mm of deposition in the baseline is 52–145 ha for the 10-year ARI events and 156–237 ha for the 50-year ARI events. These areas increase due to construction by 4–5.5 ha (3–10%) in the 10-year ARI scenario and 11–24 ha (6–15%) in the 50-year ARI scenario.

The model cells which *only* exceed 3 mm of total deposition during Project earthworks are generally on the fringe of the deposition footprints within 2 km of the Hoteo River mouth for the 10-year ARI scenarios and also spreading into each of the small sheltered sub-inlets flanking the Tauhoa River inlet and the Kakarai intertidal flats in the 50-year ARI scenario The baseline total deposition in these fringing areas is 2.8–2.9 mm but increase by 0.19-0.23 mm for the 10-year ARI scenarios and 0.37–0.41 mm for the 50-year ARI scenario (Table 12). The maximum additional deposition in any of the fringing model cells is 0.5 mm during the 50-year ARI SW scenario. Sediment deposition will not be uniform across these model cells, with preferential deposition in areas of decelerating flow and within vegetated areas.

Long-term deposition

The deposition footprint of sediment discharged from the Hoteo River is covers the upper intertidal flats and sub-inlets flanking the eastern shoreline near the Hoteo River Mouth, the tidal flats near Papakanui River and Tauhoa River estuary and near Moturimu island. The largest areas of deposition outside of Breach Point have deposition of 3–5 mm on the intertidal flats and sheltered inlets for the 10-year ARI event (Figure 30) and 5–7 mm for the 50-year ARI event (Figure 31). For both ARI events the deposition above 0.02 mm is spread throughout large areas including the upper reaches of the sheltered inlets fringing the Tauhoa River estuary and eastern shoreline of Kakarai Flats.

Measured annual sedimentation rates at a site close to the Hoteo River mouth "on the Hoteo River delta" were 21 mm/year or > 19mm/year (1959–2010), depending on dating method used (Swales et al. 2011). Approximately 2 km west of the Hoteo mouth, sedimentation rates were 6.5–6.8 mm/year (1951–2010). Swales et al. (2011) also suggest that mud will be accumulating in the mangrove forests and salt marshes that fringe the Kaipara Harbour likely more rapidly than measured on the bare intertidal flats. However, the accumulating sediment in these areas is not solely derived from the Hoteo River catchment, with 40% from marine origin as marine sands from the flood-tide delta situated at the Kaipara Harbour entrance to the west are accumulating on the Kakarai Flats (Green et al. 2017). The remaining 60% of sediment accumulating on the Kakarai Flats / Hoteo Mouth is fine sediment arising from the Hoteo River (approx. 88%) with about 10% originating from the Tauhoa River to the north, and the remaining 2% from Wairoa River in the northern Kaipara Harbour. i.e. the Hoteo River contributes in the order of 3.4 – 10 mm/year to the ASR on the Kakarai Flats/Hoteo Mouth, with the proportion of locally sourced sediment increasing with distance upstream (Gibbs et al. 2012).

The contribution of Project construction is to increase the annual average sediment load discharge by the Hoteo River from 25,600 t/year to 25,828 t/year, an increase of 228 t/year or 0.9% (see Table 6) for the 6-year bulk earthworks period. In a heuristic sense, if this 0.9% increase is linearly scaled to the measured ASR near the mouth of the Hoteo River, then the additional deposition arising from the Project is in the order of 0.034 – 0.1 mm sediment depth per year.

To further place the additional sediment loads arising from the multi-year Project construction into perspective, statistics of the modelled baseline sediment loads are shown in Table 6. Here, the natural variability in background sediment load of the Hoteo River is substantial, with a standard deviation 9,737 t/year for an annual average of 25,600 t/year over the 40-year simulation period, i.e., the standard deviation is 38% of the annual average (Catchment sediment modelling report, Sands and Clay 2019). This natural variability is large compared to the modelled increase to the annual average sediment load over the construction period (0.9% per year). Hence, the cumulative effects of the project on the long-term sediment deposition is negligible, well within natural annual variability and would be nearly impossible to measure in the field or attribute to the Project.

Overall, the coastal modelling and interpretation shows that the additional sediment load delivered to the Kaipara Harbour during Project construction results in small increases to SSC or deposition rates above the baseline situation for both short-term and long-term timeframes.

4 ORUAWHARO RIVER INPUTS: ASSESSMENT OF EFFECTS

4.1 Methodology

We estimated the likely sediment deposition patterns in the Oruawharo River estuary using existing information (e.g., Swales et al. 2011; Gibbs et al. 2012, Green et al. 2017, and others) and supplemented with a field inspection of the upper Oruawharo River.

We did not use the hydrodynamic modelling results of Green et al. (2017) even though it includes the Oruawharo River estuary. This is because we considered the model's spatial resolution in this sub-estuary as too coarse (e.g. Figure 15) to resolve the changes to sediment load arising from Project construction, and that the output could not provide level of detail required for the Marine Ecology Assessment.

We therefore used a heuristic approach to consider the potential effects of the Project on retention and dispersal of fine sediments in the Oruawharo River estuary. This approach is justified on the small quantities of additional sediment discharged to the Oruawharo River tributaries by the Project, and because there is sufficient background information available to combine with geomorphic understanding for the purposes of this assessment.

4.2 Description of the existing environment

See Section 2 for a description of the context of the wider Kaipara Harbour sedimentation regime along with available information for the Oruawharo River.

Appendix E contains full notes from our site visit to inspect the Oruawharo River and inform this assessment.

4.2.1 Description

Lower Oruawharo Arm (Kaipara Harbour to Topuni River)

The lower reaches of the Oruawharo River include a broad open expanse of intertidal mud and sand flats with a vegetated fringe (Hargraves Basin). The outflow of the 39,800 ha catchment is a narrow throat with strong tidal flows flanked by narrow mud flats and mangrove stands.

The flanks of the lower Oruawharo River are dominated by intertidal flats which are 10s – 100s m wide and are either vegetated with mangroves or remain as unvegetated mudflats. The mudflats are very soft mud with occasional outcrops of oyster beds, and occasional sand/shell beaches at the high-tide shoreline. Vegetated mud flats appear to fully occupy all side inlets excluding a narrow sub-tidal drainage channel.

Upper Oruawharo Arm (Maeneenee Creek and Te Hana Creek)

The creeks of interest are Maeneenee Creek (21.9 ha catchment) and Te Hana Creek (17.4 ha catchment) are a small part of the wider Oruawharo River system (39,816 ha catchment) and are typical examples of the numerous tidal creeks of the Kaipara Harbour. These environments are characterised by shallow, muddy and sinuous channels flanked by mud flats and mangrove stands extending to the shoreline. They are large tidal creeks, extending 10 km or more from the upper reaches to their outlets. In the uppermost reaches they become narrow freshwater-dominated creeks, with pasture grasses flanking a narrow channel with a small intertidal area and no mangroves.

4.2.2 Sedimentation rates

The existing annual sedimentation rate within the Oruawharo River estuary has been estimated at 3 mm/year (Green et al. 2017) and inferred from historic hydrographic charts to be between 3 – 17 mm/year (Murton 2000). This value is the average over the whole arm, with higher deposition anticipated in sheltered areas (e.g., mangrove forest and heads of the river/stream arms) and lower deposition in exposed reaches (e.g., Hargreaves Basin) or areas with strong currents (e.g., channels, and downstream from Hargreaves basin).

However, the accumulating sediment is not solely sourced from the local Oruawharo catchment, with 40-70% of sediment coming from the Wairoa River catchment and trace sediment from the Hoteo River (Gibbs et al. 2012, Green et al. 2017).

Of the fine-sediment which is locally sourced from the Oruawharo River catchment, approximately 5% leaves the sub-estuary with the remainder dispersed around the sub-estuary (Reeve and Green, 2016).

For the purposes of this assessment we assume a background baseline ASR of 6 mm/year arising from all sediment sources. We attribute 60% of this annual sedimentation to the Oruawharo River catchment (i.e. 40% imported from other catchments) and neglect the 5% loss of locally derived sediment. Therefore, the assumed existing ASR arising only from the locally-sourced sediments is approximately 3.6 mm/year on average over the whole arm.

4.3 Sediment inputs from catchment sediment model

The sediment loads for the Oruawharo River catchment are shown in Table 1 (p. 21) for the short-term events, with the long-term sediment loads and annual statistics shown in Table 6 (p. 24) and Table 7 (p. 24).

4.4 Description of the fate of upstream sediment inputs

4.4.1 Existing environment

The Oruawharo River estuary of the Kaipara Harbour is a depositional environment for sediment with the existing primary depositional areas sketched in Figure 32. The mapped areas include the sheltered areas (intertidal flats, sheltered inlets) and around the fringes of exposed reaches (Hargreaves Basin

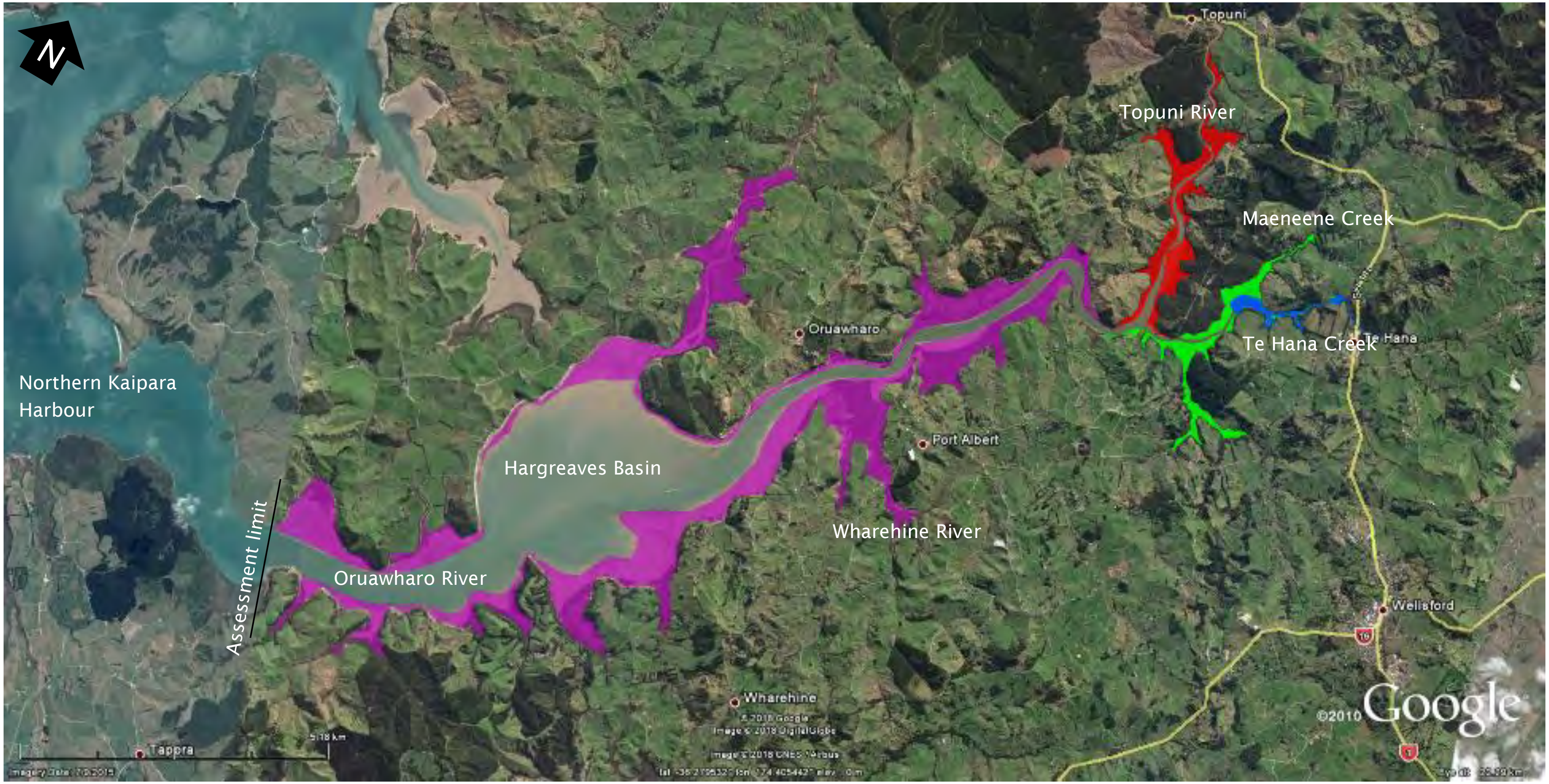

Figure 32: Primary depositional areas of Oruawharo River estuary. [Deposition areas manually sketched for the Lower Oruawharo River (purple), Topuni River sub-estuary (red), Maeneene Creek sub-estuary (green) and Te Hana Creek sub-estuary (blue)].

Sediment-laden freshwater discharged into the headwaters of Oruawharo River tributaries will not be solely trapped within the upper sub-estuaries of each creek. During discharge events, some sediment will be distributed over the localised intertidal flats near the creek mouths where it will settle and accumulate, the remainder will be conveyed downstream within the sub-tidal channels to be mixed into the broader body of the Oruawharo River estuary. Once here, the tidal currents, river currents and waves act to mix, flocculate, settle, resuspend, disperse and transport the sediment load around the wider estuary, distributing the sediments widely and into other river sub-estuaries (e.g., Topuni and Wharehine Rivers) but at lower concentration than near the original upstream input. On subsequent flood tides the sediment-laden waters are returned to more sheltered environments where the shallow water and dense vegetation promotes deposition of sediment onto the intertidal flats.

Substantial deposition is not anticipated in exposed open reaches (Hargreaves Basin) or areas scoured by rapid currents (entrance throat and the main sub-tidal channel).

Upstream in the uppermost reaches of the estuaries and into the freshwater stretch of the creeks (i.e., upstream of the mangrove limit), sediment transport is dominated by stream flow and is not a depositional environment for fine sediments. These creeks are narrow and shallow with steep streambanks and no floodplain (e.g. Figure 131, Appendix E). The creeks have little capacity to intercept suspended sediments or room to accommodate deposited sediments. Some sediment will settle as the flow stagnates by the backing up of tidal waters, but this is only temporary as it is subsequently flushed by higher currents during ebb tides. Streambeds are further flushed following rainfall events.

4.4.2 Effect of the Project

Short-term

Table 13 shows estimated additional deposition arising from the Project for 2-, 10- and 50-year ARI events, assuming uniform deposition over the primary depositional areas (see Figure 32) of either A) the local sub-estuary only or B) wide distribution around the Oruawharo River estuary. We have neglected the 5% loss of sediment into the body of the Kaipara Harbour for simplicity, resulting in a conservatively-high (by 5%) sedimentation rate estimate.

A) If all catchment-derived sediment is retained within the local receiving sub-estuaries. In this case the total deposition depth is < 1.2 mm for the baseline and the increase to sedimentation attributable to Project is less than 0.3 mm for all ARI scenarios (Table 13). For example, in the Te Hana Creek receiving environment (27 ha) where the percentage increase in sediment load is greatest (21% for the 50-year ARI event – see Table 1), the increase in average deposition is 0.26 mm above the baseline deposition of 1.17 mm, resulting in total deposition of 1.43 mm

B) If all catchment derived sediment is uniformly dispersed around the wider Oruawharo River estuary, including the local receiving sub-estuaries. In this case the total deposition for a 50-year ARI event is 0.64 mm with an increase of 0.02 mm attributable to increased sediment load during Project earthworks.

Overall the increase to average deposition depth will therefore be between 0.02 mm and 0.26 mm for the 50-year ARI events, and less than 0.1 mm depth for both the 10- and 2-year ARI events (Table 13), well below the 3 mm threshold in all cases. In practice, deposited sediment will be distributed over the entire receiving environment but with preferential deposition will occur closer to the source, in locations where flow decelerates (i.e., the fringe of the mangroves), and in the most sheltered areas with no waves or strong currents.

Following the same rationale as Table 13, in order for the additional sediment load of 111 t (Te Hana Creek, 50-year ARI – see Table 1) to cause the total deposition rate to exceed the ecological threshold of 3 mm requires an additional deposition of 1.83 mm (3 mm minus 1.17 mm) to be concentrated over an area of 3.8 ha (approximately a 200 m by 200 m square) which is about 15% of the total Te Hana sub-estuary area. This degree of concentration of all additional sediment arising from Project construction is unlikely in the sub-estuaries relevant to the Project with greater dispersal expected. This further suggests that sediment deposition arising from short-term events is unlikely to approach the threshold for ecological impacts.

Table 13: Potential sediment deposition depth within the Oruawharo estuary and sub-estuaries. Deposition assumes uniform distribution over depositional area at density[6] of 1600 kg/m^3. Refer to Table 1 for sediment loads in each event. Area of receiving environment extracted from Google Earth polygons of Figure 32.

Catchment / sub-estuary name	Event	Area of receiving environment (ha)	Average deposition (mm)			Description
			Baseline	**Construction (year 1-2)**	**Increase**	
Oruawharo estuary	2-year ARI	521	0.21	0.21	0.00	100% dispersal to wider Oruawharo estuary.
	10-year ARI		0.41	0.42	0.01	
	50-year ARI		0.64	0.66	0.02	
Maeneene Creek	2-year ARI	120	0.06	0.06	0.00	100% retention within Maeneenee Creek sub-estuary.
	10-year ARI		0.11	0.11	0.01	
	50-year ARI		0.17	0.20	0.03	
Te Hana Creek	2-year ARI	27	0.45	0.46	0.02	100% retention within Te Hana Creek sub-estuary.
	10-year ARI		0.83	0.92	0.09	
	50-year ARI		1.17	1.43	0.26	

We expect that the additional sediment load arising from the Project will be sufficiently diluted below the concentration-time ecological threshold (0.08 kg/m^3 for 72 continuous

[6] For this calculation we assume a deposited bulk density of 1600 kg/m^3 based on measured bulk density values from 1490 kg/m^3 to 1980 kg/m^3 in the top 50-cm of the cores from the nearby Arapoao Arm in the northern Kaipara Harbour (Swales et al. 2016).

hours) because of flood-flow flushing and dilution around the subestuary. Hence, the increase in sediment load is not expected to result in SSC levels substantially higher than for baseline events or for a longer duration than baseline events.

Therefore, for all short-term storm-event sediment discharges the deposition of sediment arising from the Project will be well below the 3 mm per ecological threshold. Further, the small increase in sediment load is not expected to result in substantially higher SSC levels or longer periods of elevated SSC compared to the baseline events.

Long-term

The existing annual average sediment load into the Oruawharo River (at mouth) is 9,284 t/year as determined over the 40-year time catchment sediment model period (Table 6, p. 24). The Project is expected to increase the sediment load by 18 t/year for years 1-5 and only 2 t for the final year of bulk earthworks. This predicted increase in sediment load is, on average, 0.16% over the multi-year construction period.

Linear scaling of the 0.16% increase in Project construction sediment load suggests the additional deposition arising from the Project is about 0.006 mm/year on average above the total baseline ASR of 6 mm/year. This assumes the local-catchment contributes 3.6 mm/year to the 6 mm/year ASR (see description of the existing environment, Section 4.4.1) which arises from the annual average sediment load in this catchment. This potential long-term sedimentation arising from Project construction is negligible (<0.1%) compared to the existing baseline ASR.

To further place the additional sediment loads arising from the multi-year Project construction into perspective, statistics of the modelled baseline sediment loads are shown in Table 6 (p. 24). Here, the annual variability in sediment load of the Oruawharo River is substantial, with a standard deviation 3,800 t/year for an annual average of 9,284 t/year over the 40-year simulation period, i.e., the standard deviation is 41% of the annual average (Table 6). This natural variability is large compared to the modelled increase to the annual average sediment load over the construction period (0.16%). Hence, the cumulative effects of the project on the long-term sediment deposition is negligible, well within natural annual variability and would be nearly impossible to measure in the field or attribute to the Project.

As outlined in the short-term assessment, the additional sediment delivered by the Project over the multi-year construction window will not be uniformly deposited around the wider Oruawharo River estuary. Sediment will be concentrated within the existing primary depositional areas (outlined in Figure 32) including the sheltered areas (intertidal flats, sheltered inlets) and around the fringes of exposed reaches (Hargreaves Basin). The highest deposition rates are expected within the most sheltered mangrove stands.

Although the slow infilling of Hargraves Basin has been documented (Murton 2000), the exposed sand flats of Hargraves Basin will not be smothered by the small increase in fine sediments supplied by the Project. Infilling of Hargreaves Basin is expected to continue by gradual deposition at the fringes and sheltered inlets by reworking of existing sediments in the estuary and slow flushing of sediment from this and other catchments. However, some temporary deposition may occur during calm periods within Hargreaves Basin, until the wind rises and waves resuspend sediments and currents transport sediment to more sheltered areas within the estuary where they settle to the seabed.

4.5 Summary

Overall, the additional sediment discharged into the headwaters of the Oruawharo River by Project construction is a small proportion of the base sediment load for short-term storm events and a small proportion of the long-term annual variability in sediment load. In the long-term and short-term assessment there will be small to negligible increases to sediment deposition rates throughout the estuarine receiving environment. Where sediment does settle to the seabed it will not be uniformly distributed throughout the Oruawharo River with preferential deposition closer to the source, in locations where flow decelerates (i.e., the fringe of the mangroves), and in the most sheltered with no waves or strong currents. Predicted deposition rates are expected to be well below the 3 mm ecological threshold in all areas. The small increase in sediment load is not expected to result in materially higher SSC or longer periods of elevated SSC.

5 SUMMARY

This report has addressed the fate of fine sediments discharged to the Kaipara Harbour by the proposed Project. Specifically, discharges to the Hoteo River catchment which flows into the southern harbour, and discharges to the upper creeks of the Oruawharo River which flows into the northern harbour.

The coastal modelling shows that the additional sediment load delivered by the Hoteo River into to the Kaipara Harbour during Project construction results in small increases to sediment deposition thickness and SSC above the baseline situation for both short-term and long-term timeframes. The increases to sediment deposition thickness and SSC are similar magnitude to the increase in sediment load caused by Project earthworks - which is 12% above the baseline sediment load for the 50-year ARI event, and 0.9% on average over the construction period. The areas which exceed ecological thresholds are within the immediate vicinity of the Hoteo River Mouth and intertidal flats to the north and south.

The additional sediment discharged into the headwaters of the Oruawharo River by Project construction is a small proportion of the base sediment load and much smaller than the annual variability in sediment load. There will be small to negligible increases to both short-term and long-term sediment deposition rates within the estuary, with predicted deposition well below the 3 mm ecological threshold in all areas. The small increase in sediment load is not expected to result in materially higher SSC levels or longer periods of elevated SSC.

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APPENDIX A: FRESHWATER AND SEDIMENT INPUTS: METHOD

The sediment transport model requires inputs of river discharge (m^3/s) and SSC (g/m^3). However, data for modelling were provided as daily values of freshwater discharge (m^3/day) and sediment load (t/day) as matched to a historic storm event at each ARI. This temporal resolution is too coarse for the hydrodynamic model, which operates at 5-minute timesteps.

Timing

At the daily timesteps of the data provided, the peak of the sediment load preceded the hydrograph peak by exactly 24 hours. However, when converting sediment load to sediment concentration the 24 hour delay resulted in unrealistically high SSC during the beginning of the event.

Therefore, in order to appropriately simulate flow, load and SSC for the design events the timing of sedigraph and hydrograph peaks was altered. The alterations to the timing of each peak was based on observations from 7 storm events from 2012–2014. In these events, the delay between sedigraph peak and hydrograph peak in the Hoteo River was between 6 and 24 hours, with an average of 10 hours (pers. comm. Andrew Hughes, NIWA). Therefore, the modelled sedigraph and hydrograph peaks were offset by about 10 hours, which ensures suspended sediment concentration remains within acceptable levels while retaining the correct sediment loads.

Freshwater

Realistic sub-daily freshwater flows were created by scaling the hydrographs from the same historical storm events, but at higher resolution by using measured flow data in the Hoteo River. The scaling was undertaken to match the cumulative discharge over the storm event. The scaling is not uniform in time to better match the flow provided at daily timesteps. An example of flow scaling is given in Figure 33 and Figure 34. This method ensured that the freshwater inputs over duration of the event were the same whether at daily or sub-daily timesteps.

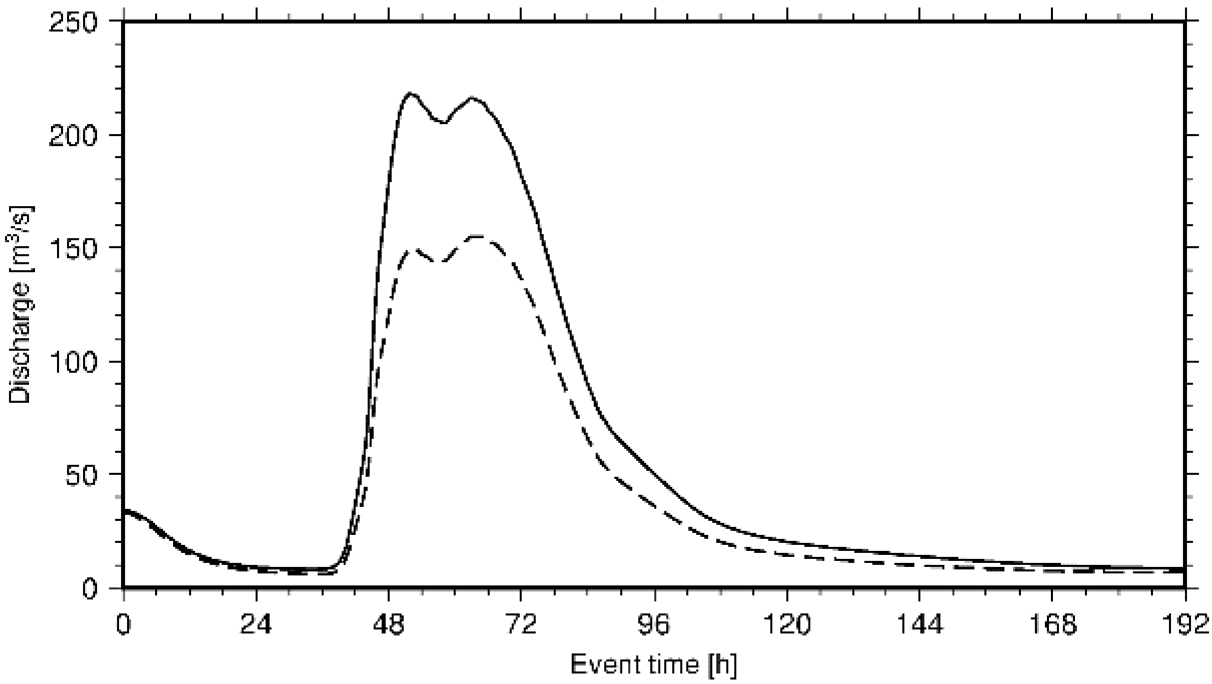

Figure 33: Comparison of original and scaled hydrograph for the 10-year ARI event. The dashed line is the historical flow event of the 23/09/2013 and the black line is the scaled event.

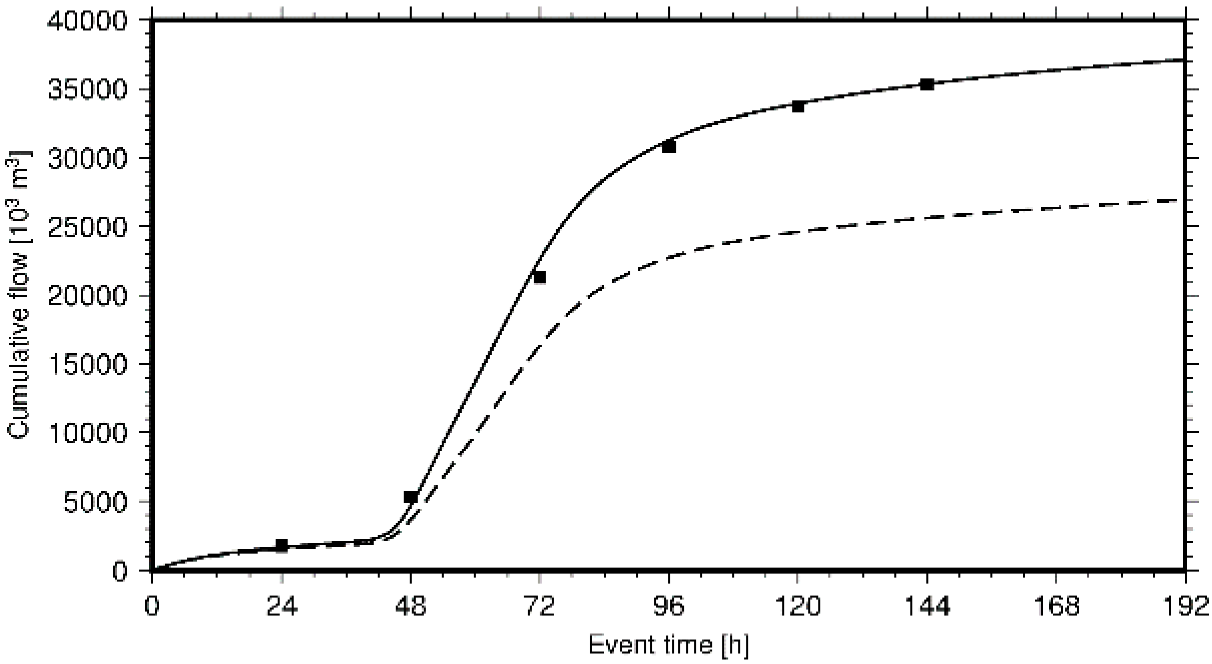

Figure 34: Example of cumulative flow scaling. The dashed-line is the historical event of reference used to scale the daily flow provided (reference event began on the 23/09/2013).

Sediment load

The method to produce SSC inputs to the model was adjusted from the flow scaling method so that sediment load inputs to the model (as SSC, in kg/m^3) were compatible with the provided sediment loads (t/day).

In this case, a distribution was fitted to the cumulative daily sediment load. The distributions were adjusted to follow the daily loads while precisely matching the total event sediment load. The fitting was constrained so that SSC remained within reasonable limits (< 3 kg/m^3) of sediment loads for such large storm events. For the 10-year ARI event an exponential fit was used to scale the rise of the sediment load and a log distribution was used to match the falling of sediment load input (Figure 35). For the 50-year ARI event a beta distribution was used to fit the cumulative sediment load (Figure 36). The goal of this distribution fitting was to manipulate sediment inputs to the model in a way that best represented the supplied data.

The time derivative of the cumulative sediment load curve was then used to produce the sediment concentration timeseries for modelling (see Figure 18 and Figure 19 on page 46).

Note that the scaling procedure produces an artefact of high background SSC prior to the 50-year ARI events (0.450 kg/m^3). The high SSC is caused by multiplying a low river discharge (2.2 m3/s) prior to the rainfall influx with the pre-event sediment load data from Jacobs. The high SSC is inconsequential to the downstream modelling as the flux of sediment is low (1 kg/s).

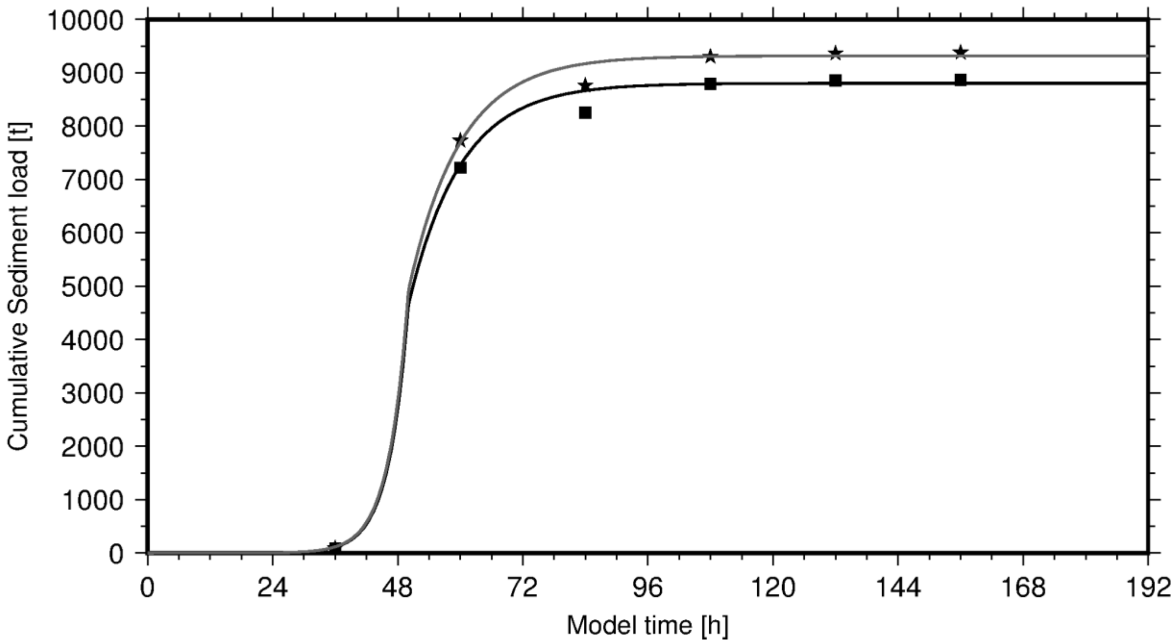

Figure 35: Fit of the cumulative daily sediment load for the 10-year ARI event. The black squares show the cumulative daily sediment load as provided for the base scenario, the black line shows the cumulative sediment load used to create the sedigraph of the Base scenario. The black stars show the cumulative daily

sediment load as provided for the construction scenario, the grey line shows the cumulative sediment load used to create the sedigraph of the construction scenario.

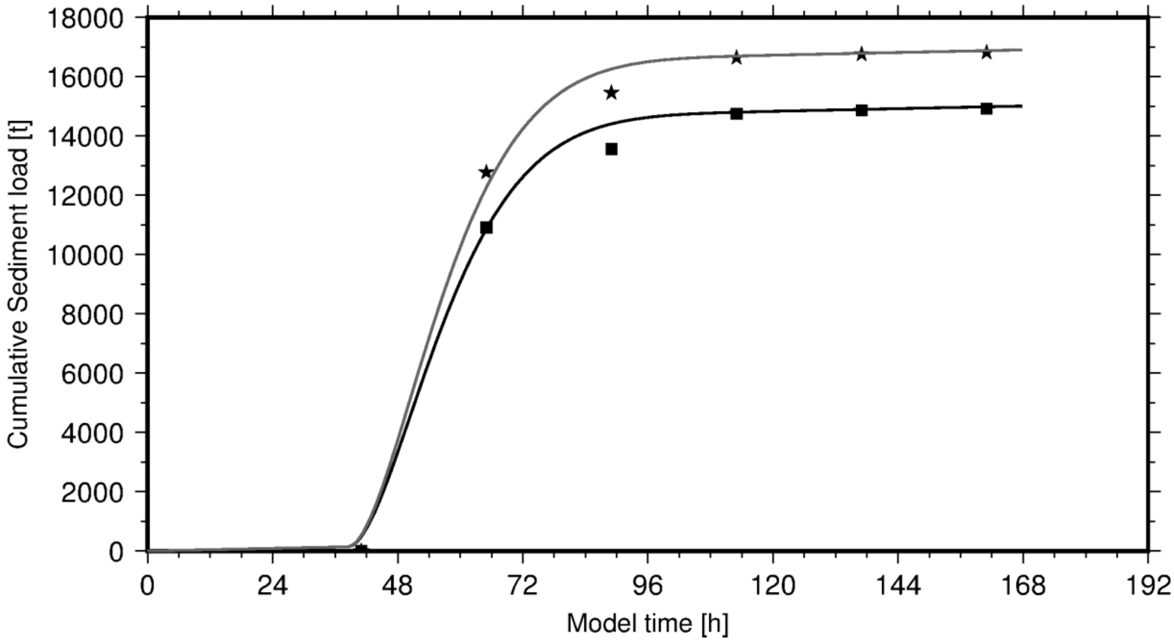

Figure 36: Fit of the cumulative daily sediment load for the 50-year ARI event. The black squares show the cumulative daily sediment load as provided for the base scenario, the black line shows the cumulative sediment load used to create the sedigraph of the Base scenario. The black stars show the cumulative daily sediment load as provided for the construction scenario, the grey line shows the cumulative sediment load used to create the sedigraph of the construction scenario.

APPENDIX B: BASELINE SIMULATION RESULTS

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Maximum SSC for baseline scenario – 10-year ARI event

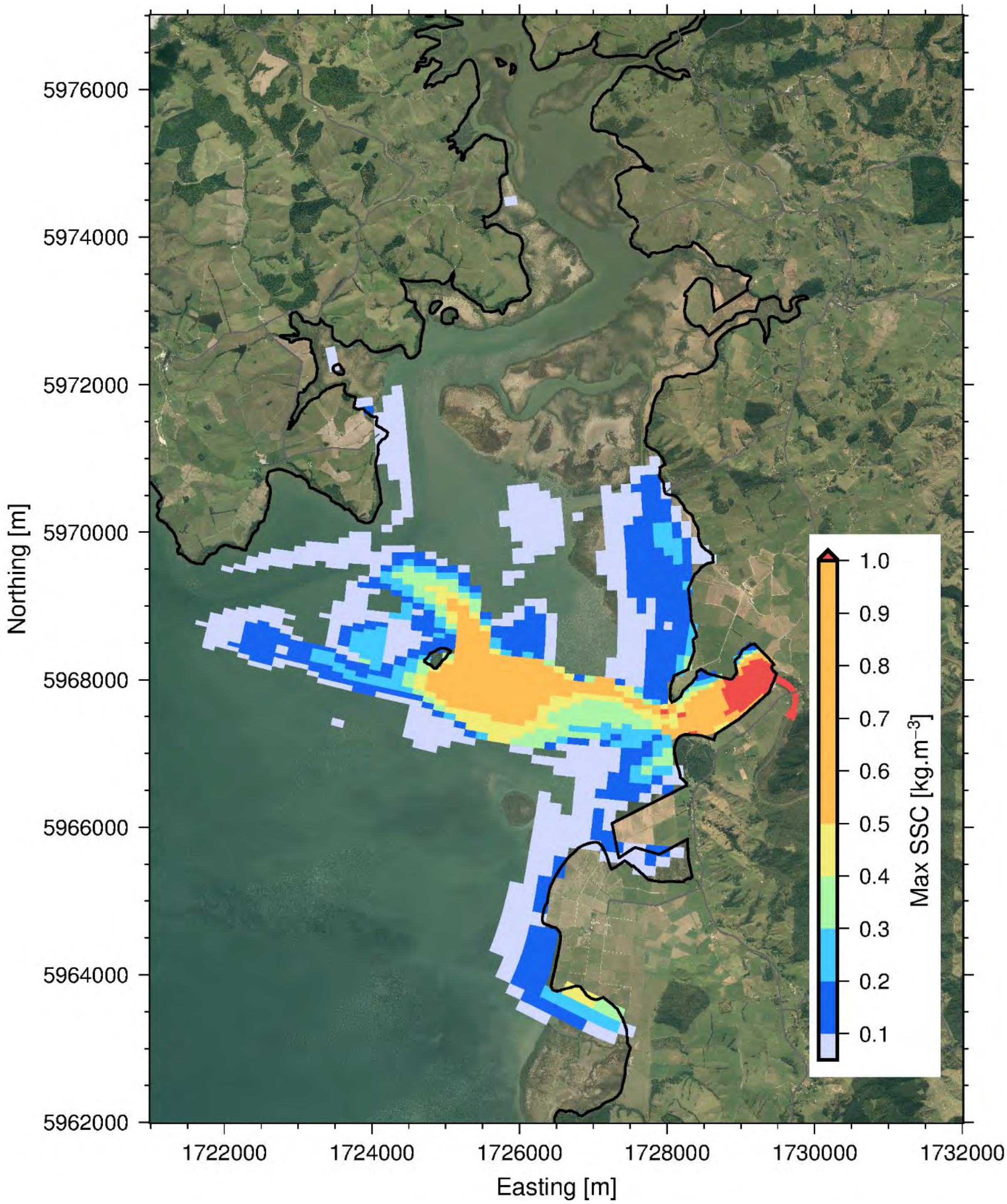

Figure 37: Maximum SSC for the base scenario of the 10-year ARI, calm wind event. Note: Sediment concentration below 0.005 kg/m^3 are not shown here.

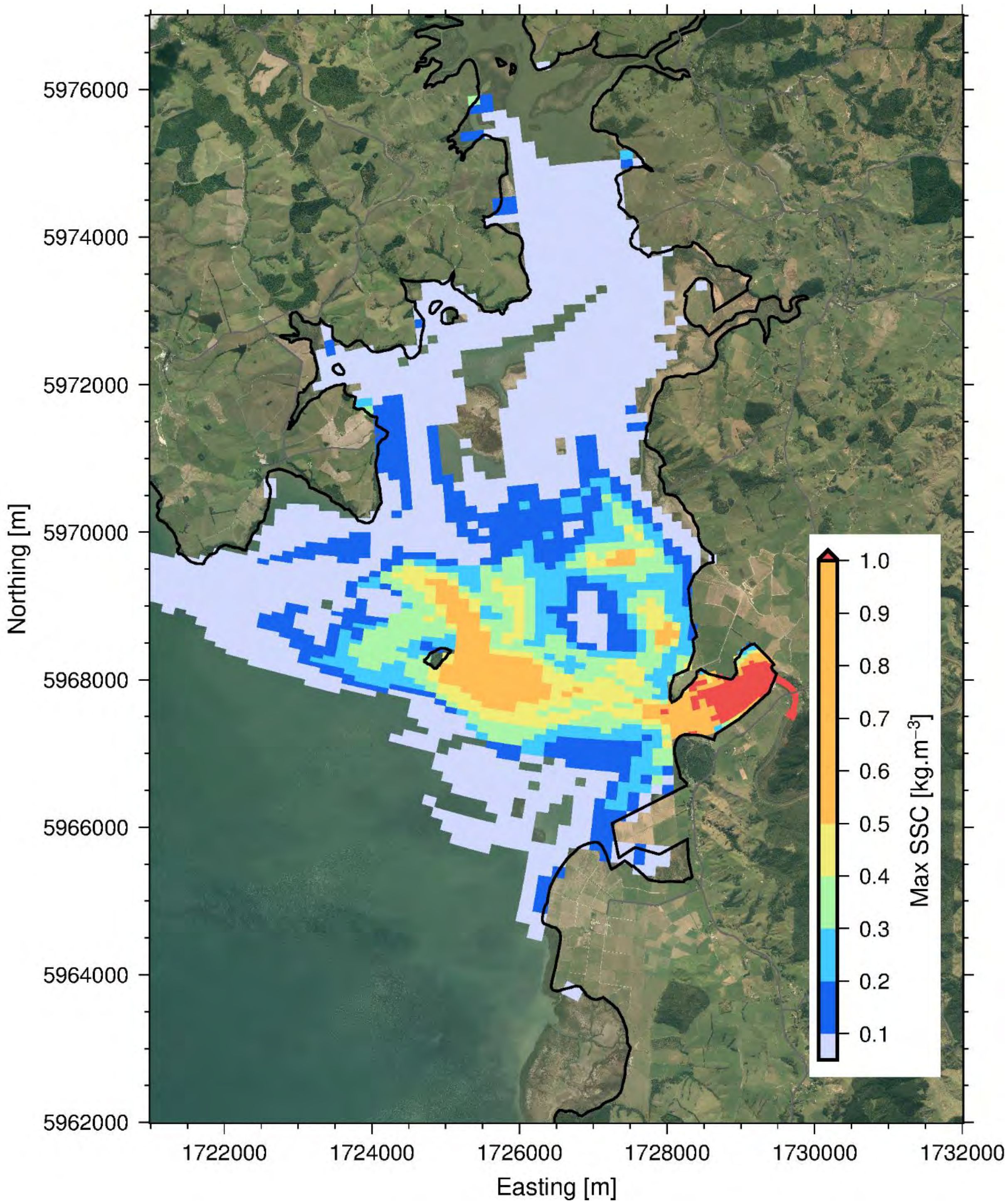

Figure 38: Maximum SSC for the base scenario of the 10-year ARI, SW wind event. Note: Sediment concentration below 0.005 kg/m^3 are not shown here.

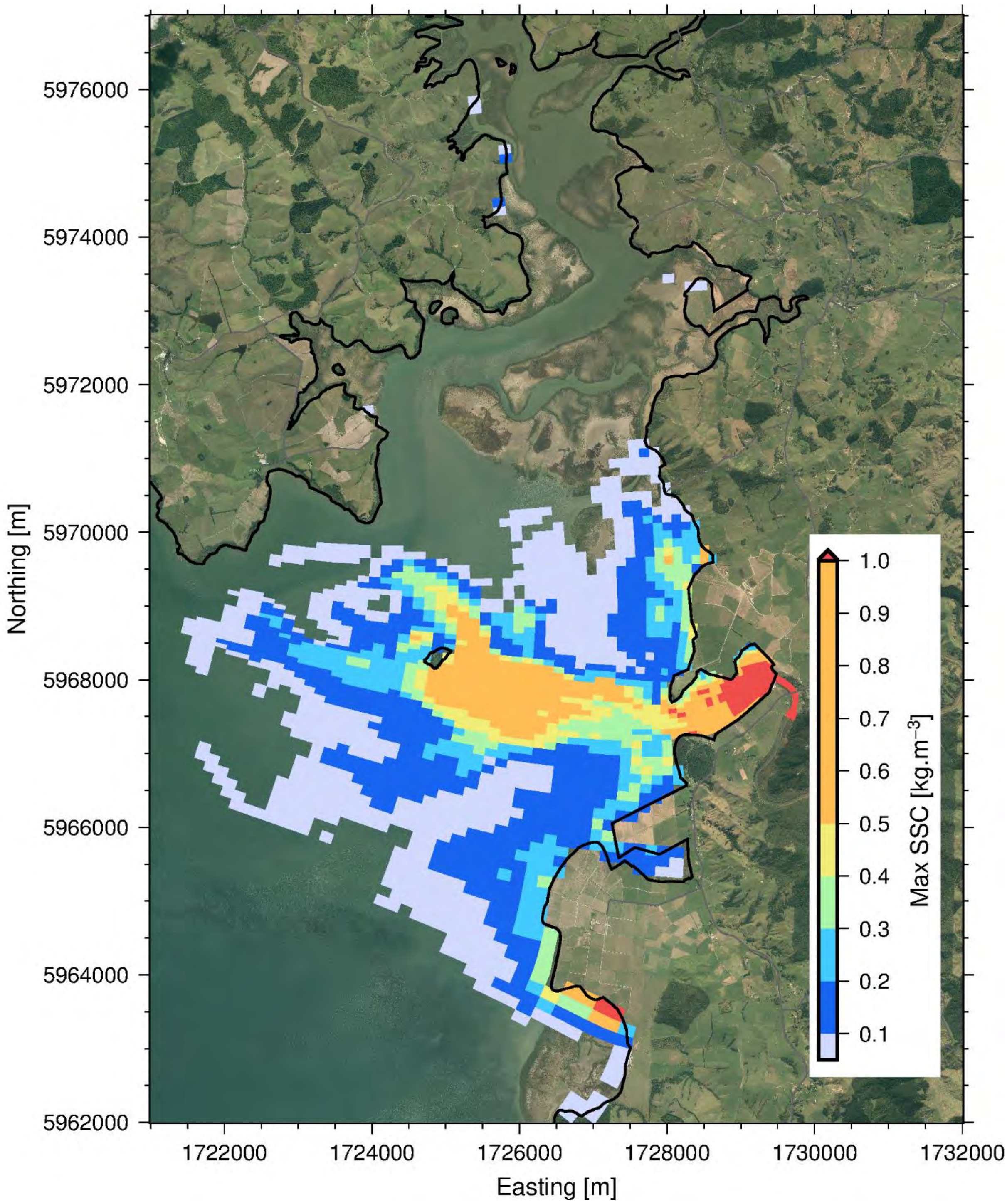

Figure 39: Maximum SSC for the base scenario of the 10-year ARI, NE wind event . Note: Sediment concentration below 0.005 kg/m^3 are not shown here.

Maximum SSC for baseline scenario – 50-year ARI event

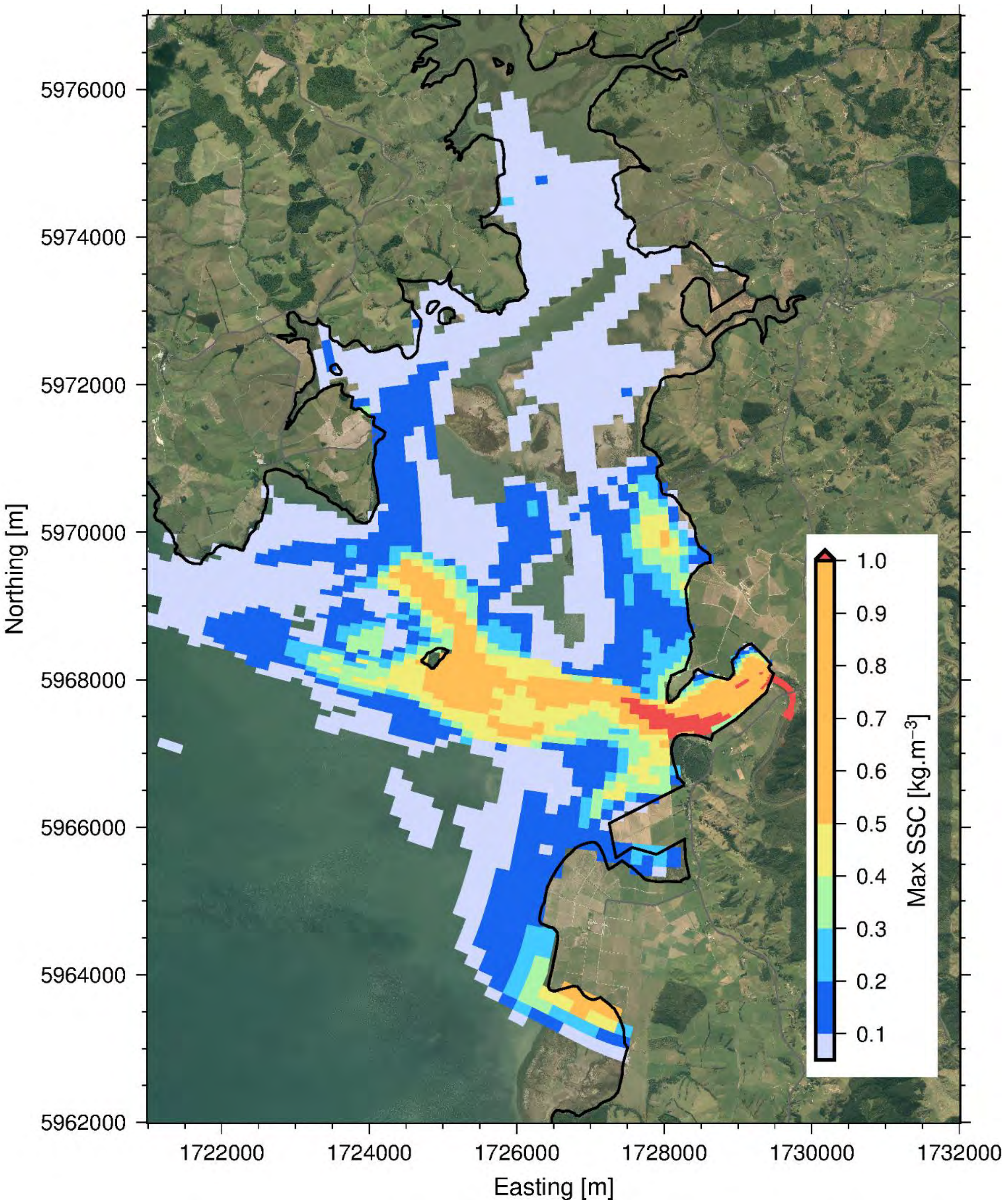

Figure 40: Maximum SSC for the base scenario of the 50-year ARI, calm wind event. Note: Sediment concentration below 0.005 kg/m^3 are not shown here.

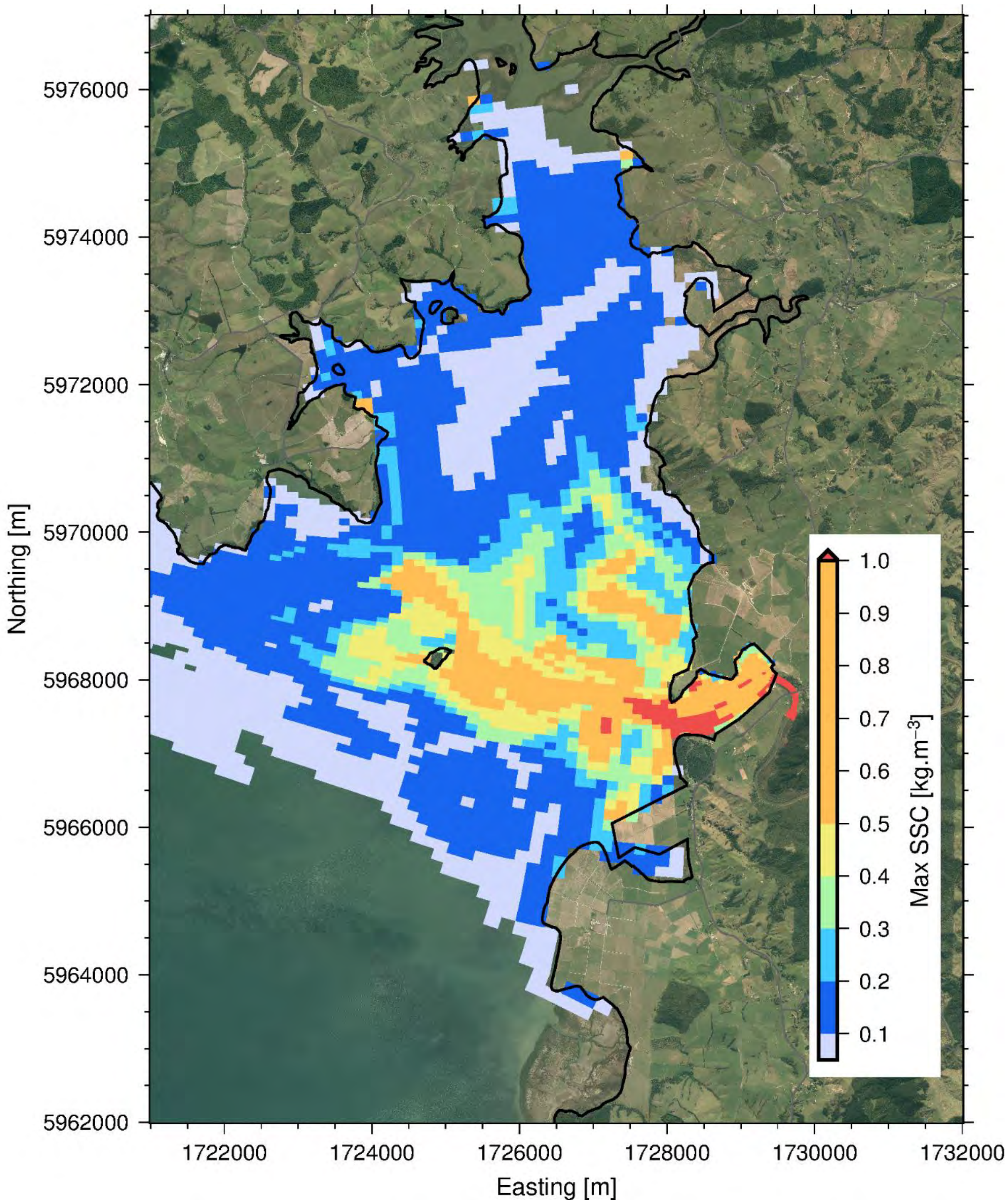

Figure 41: Maximum SSC for the base scenario of the 50-year ARI, SW wind event. Note: Sediment concentration below 0.05 kg/m^3 are not shown here.

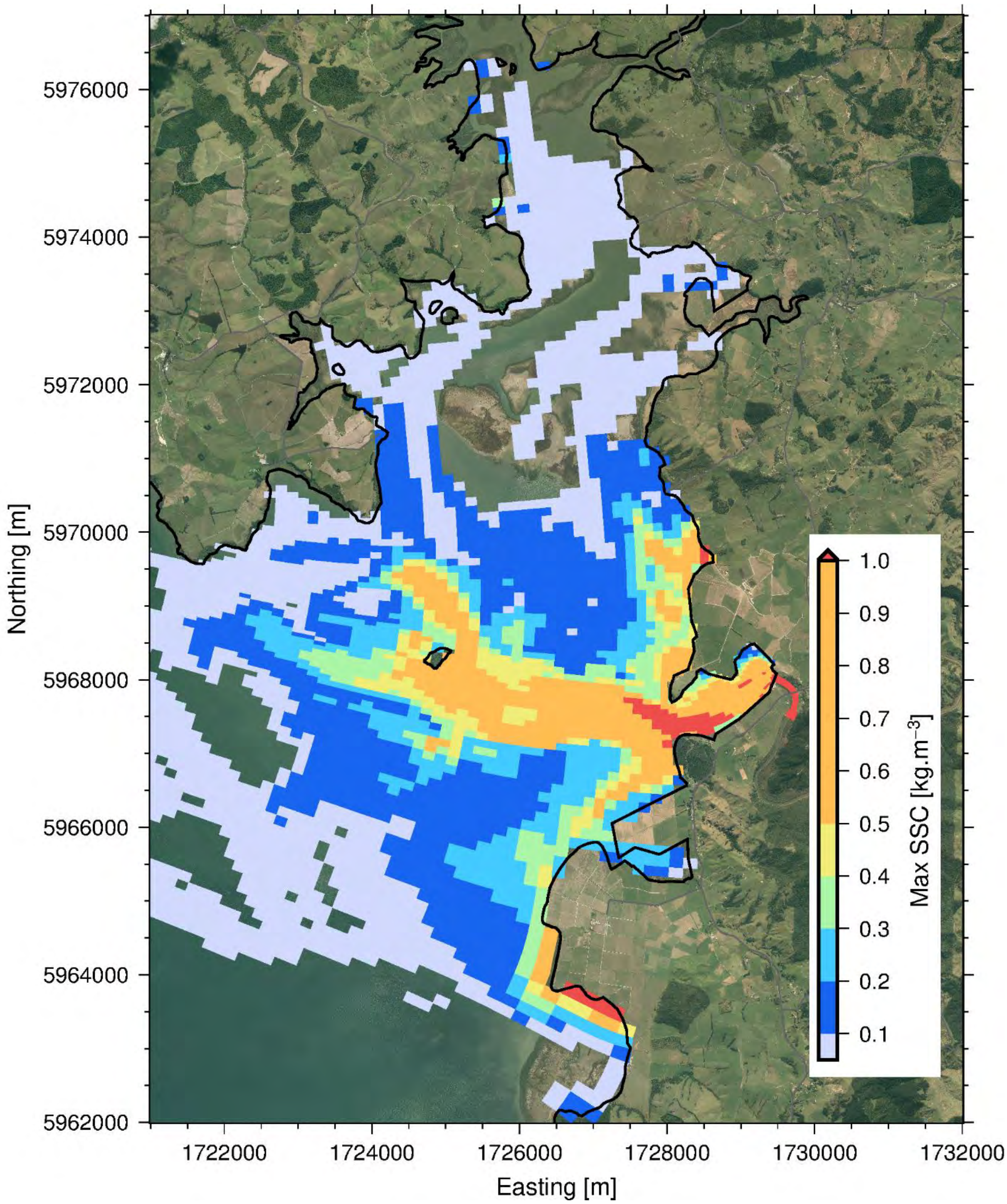

Figure 42: Maximum SSC for the base scenario of the 50-year ARI, NE wind event. Note: Sediment concentration below 0.005 kg/m^3 are not shown here.

Sediment concentration 1 day after the start of the event for the baseline 10-year ARI event

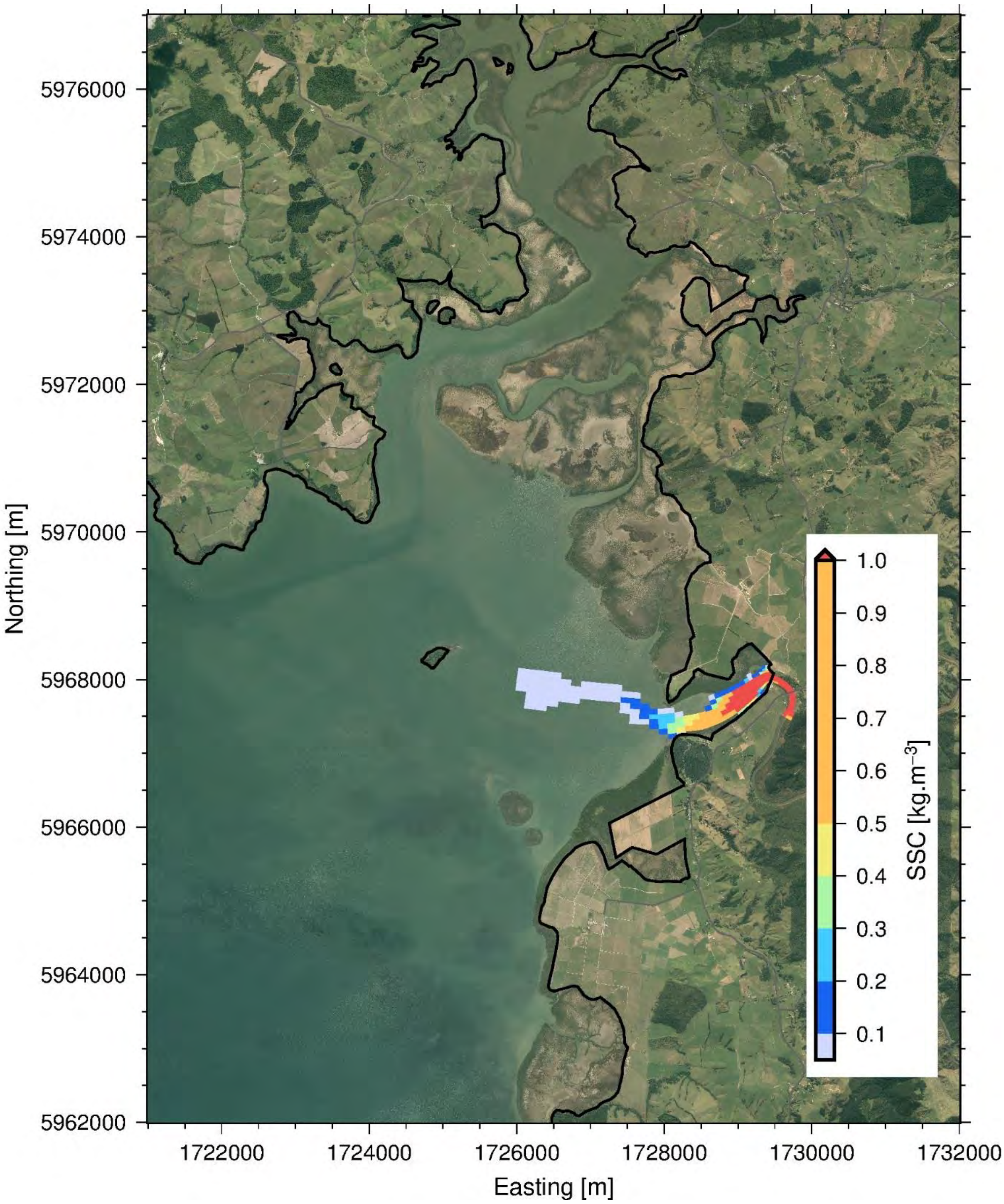

Figure 43: Suspended sediment concentration 1 day after the start of the event for the baseline 10-year ARI, calm wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

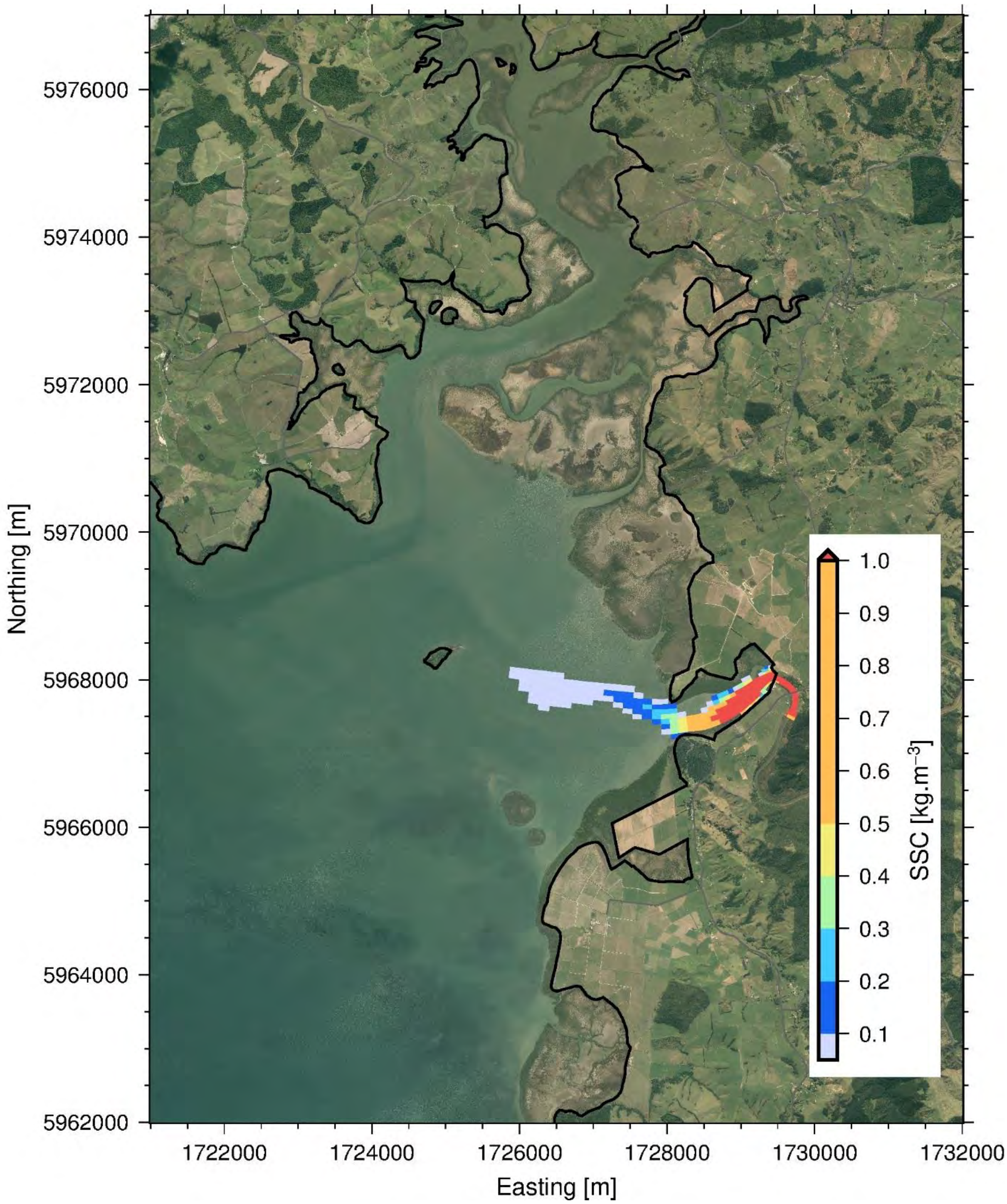

Figure 44: Suspended sediment concentration 1 day after the start of the event for the baseline 10-year ARI, SW wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

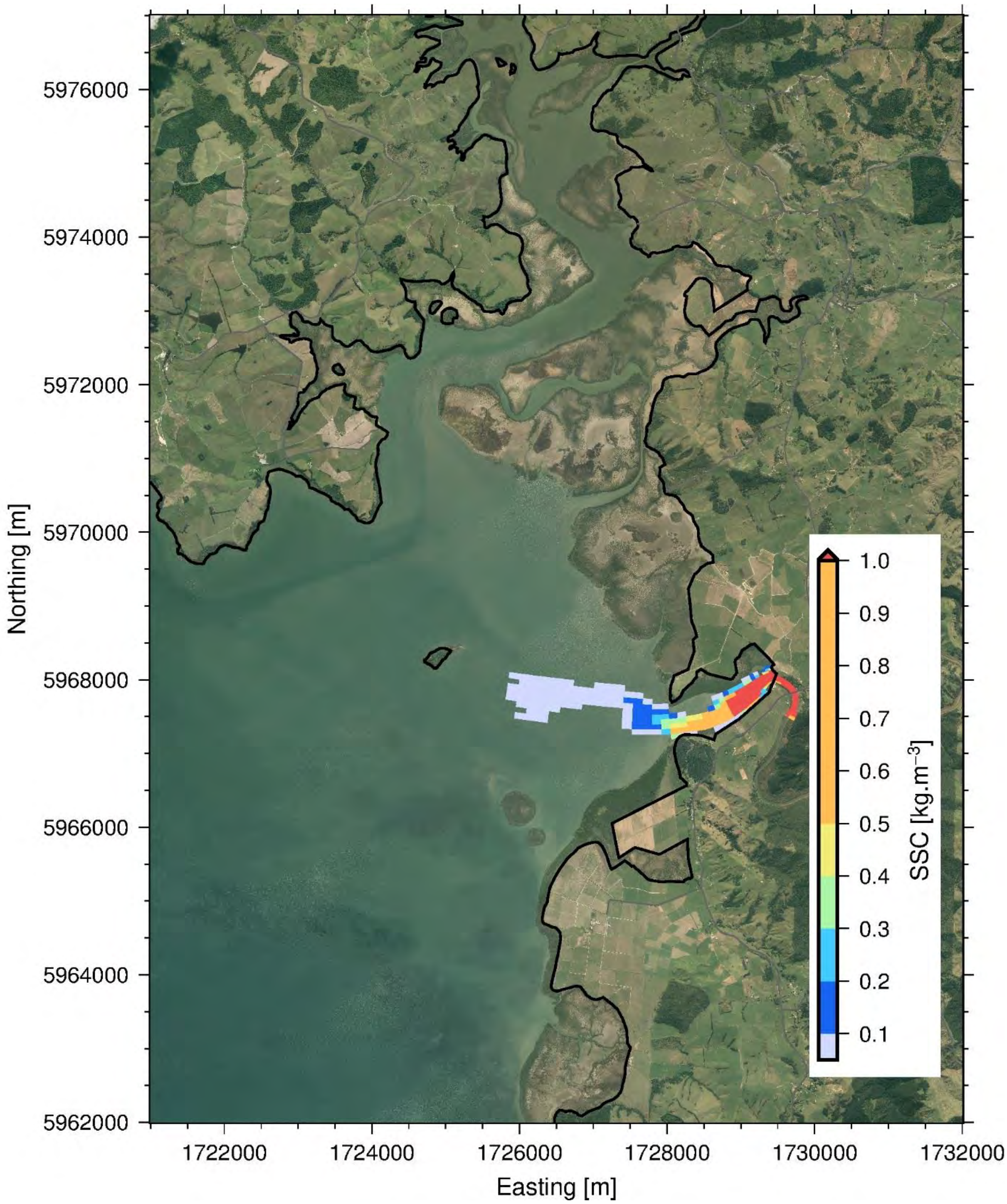

Figure 45: Suspended sediment concentration 1 day after the start of the event for the baseline 10-year ARI, NE wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

Suspended sediment concentration 3 days after the start of the event for the baseline 10-year ARI event

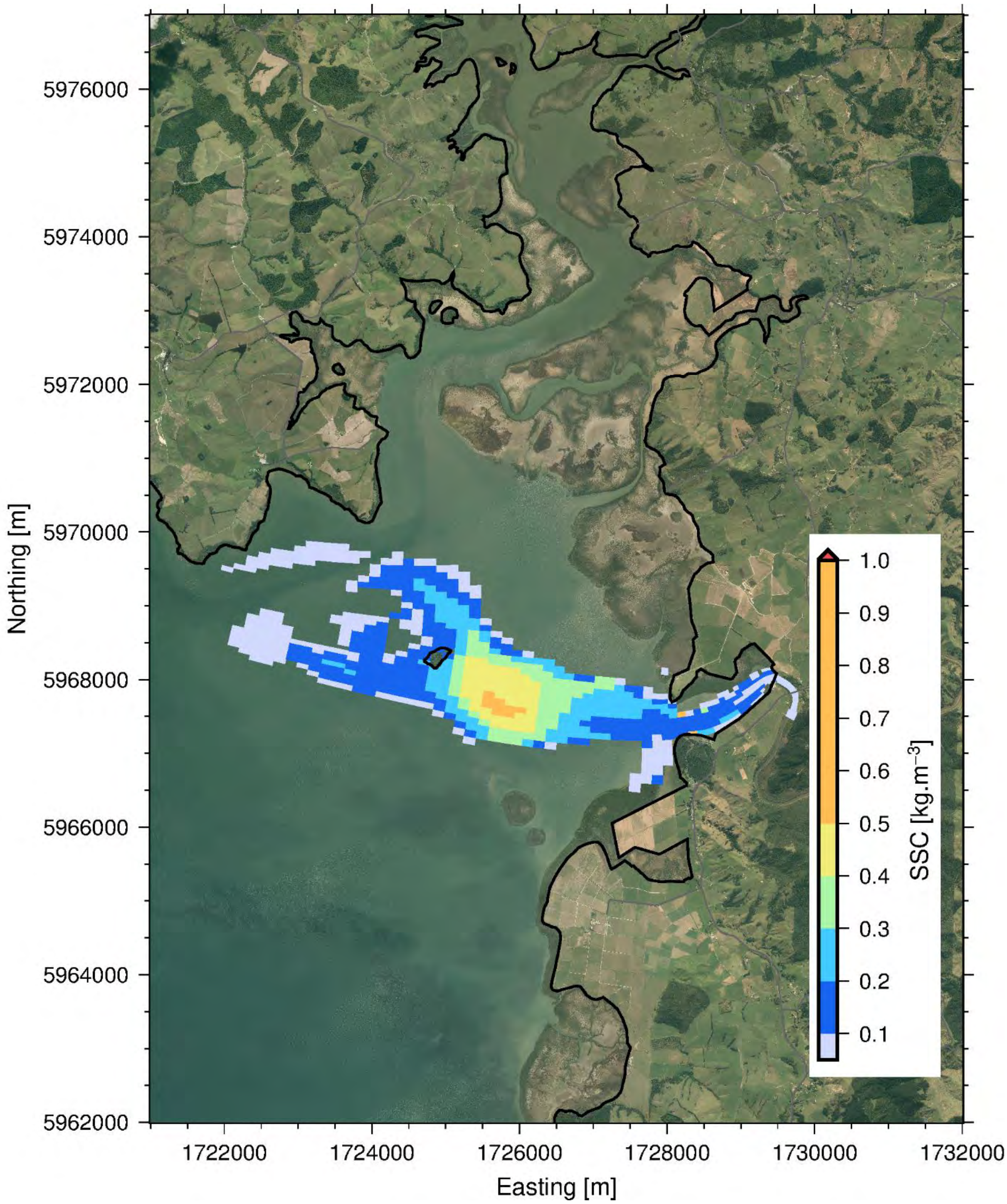

Figure 46: Suspended sediment concentration 3 days after the start of the event for the baseline 10-year ARI, calm wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

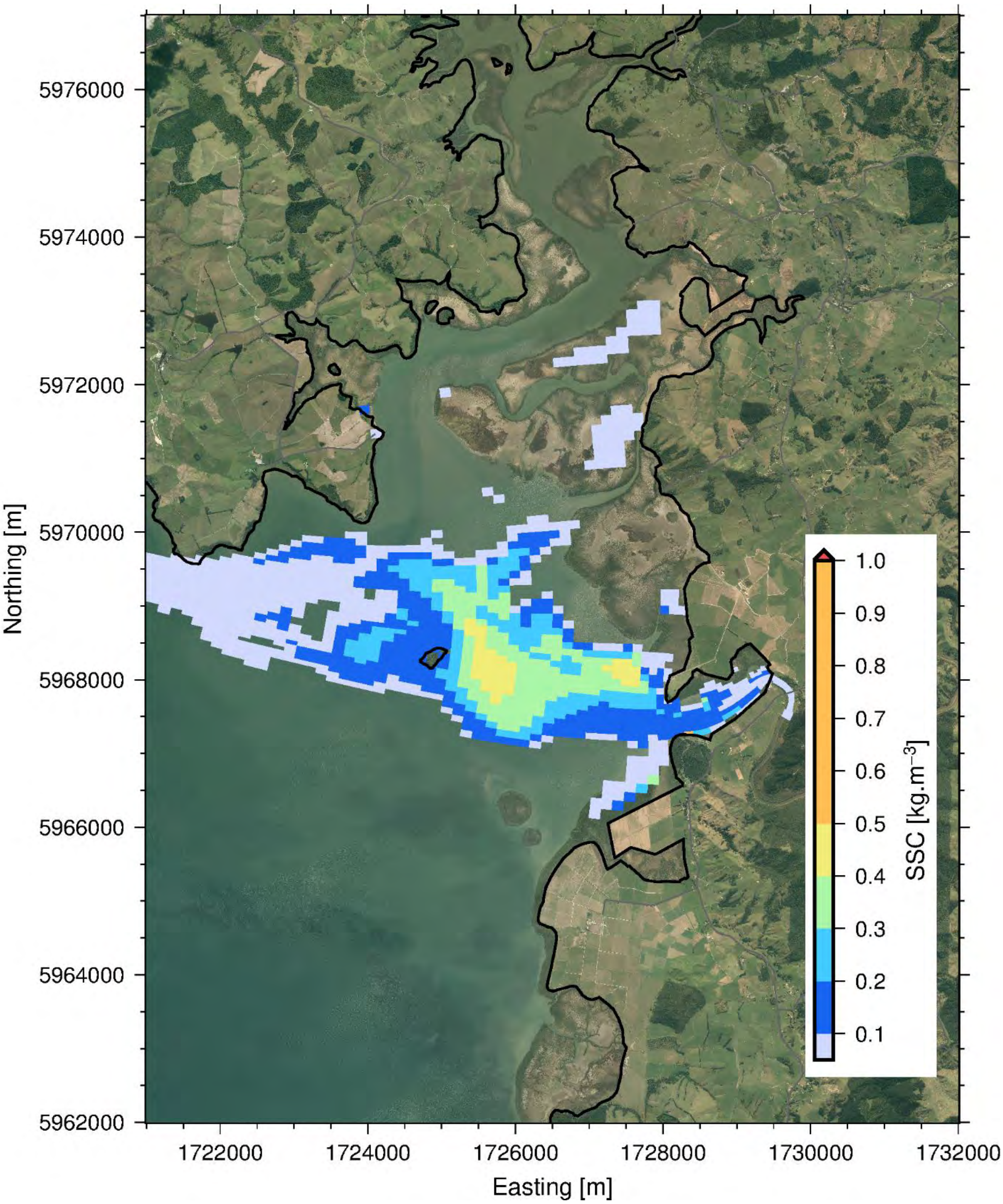

Figure 47: Suspended sediment concentration 3 days after the start of the event for the baseline 10-year ARI, SW wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

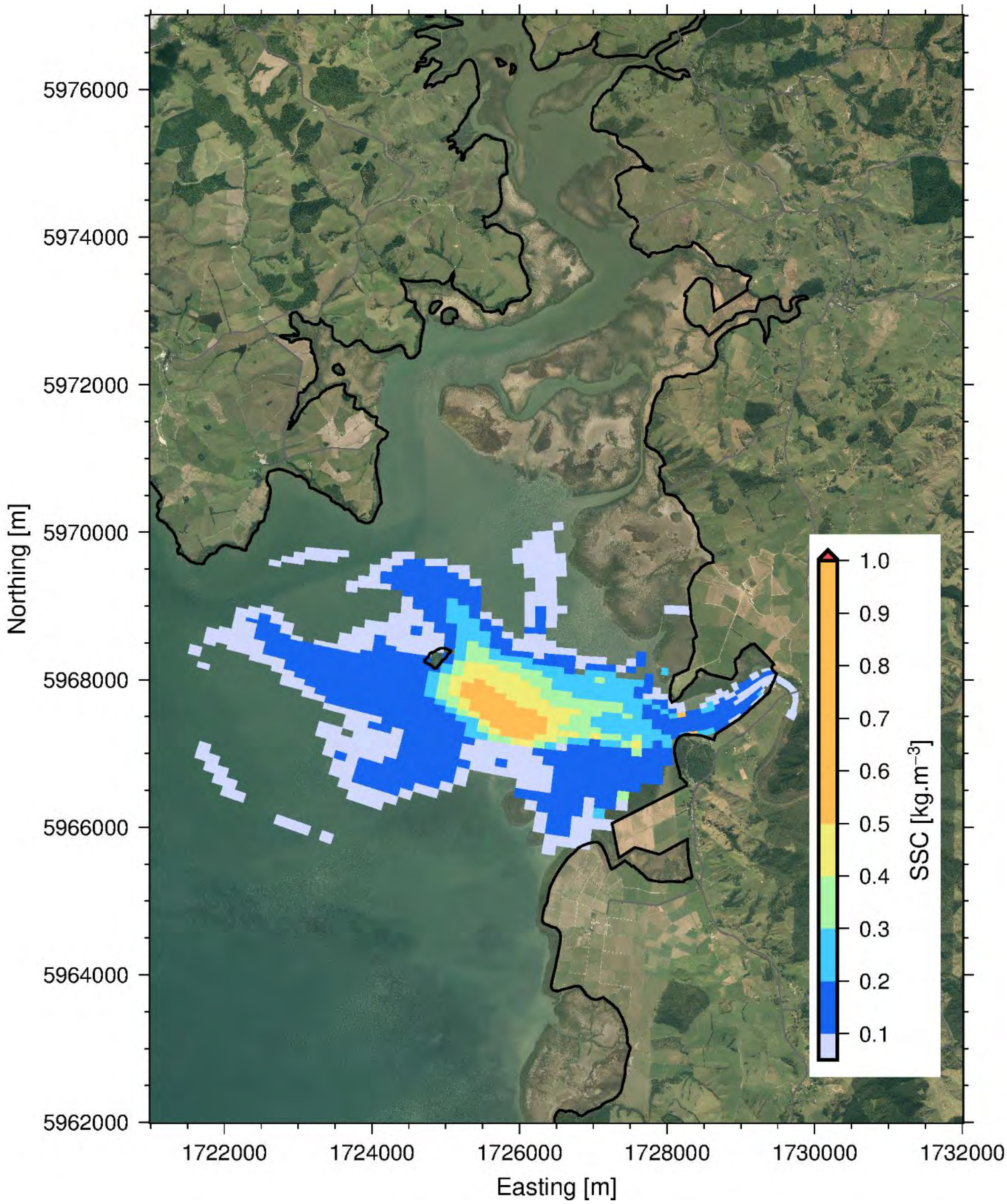

Figure 48: Suspended sediment concentration 3 days after the start of the event for the baseline 10-year ARI, NE wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

Suspended sediment concentration 1 day after the start of the event for the baseline 50-year ARI event

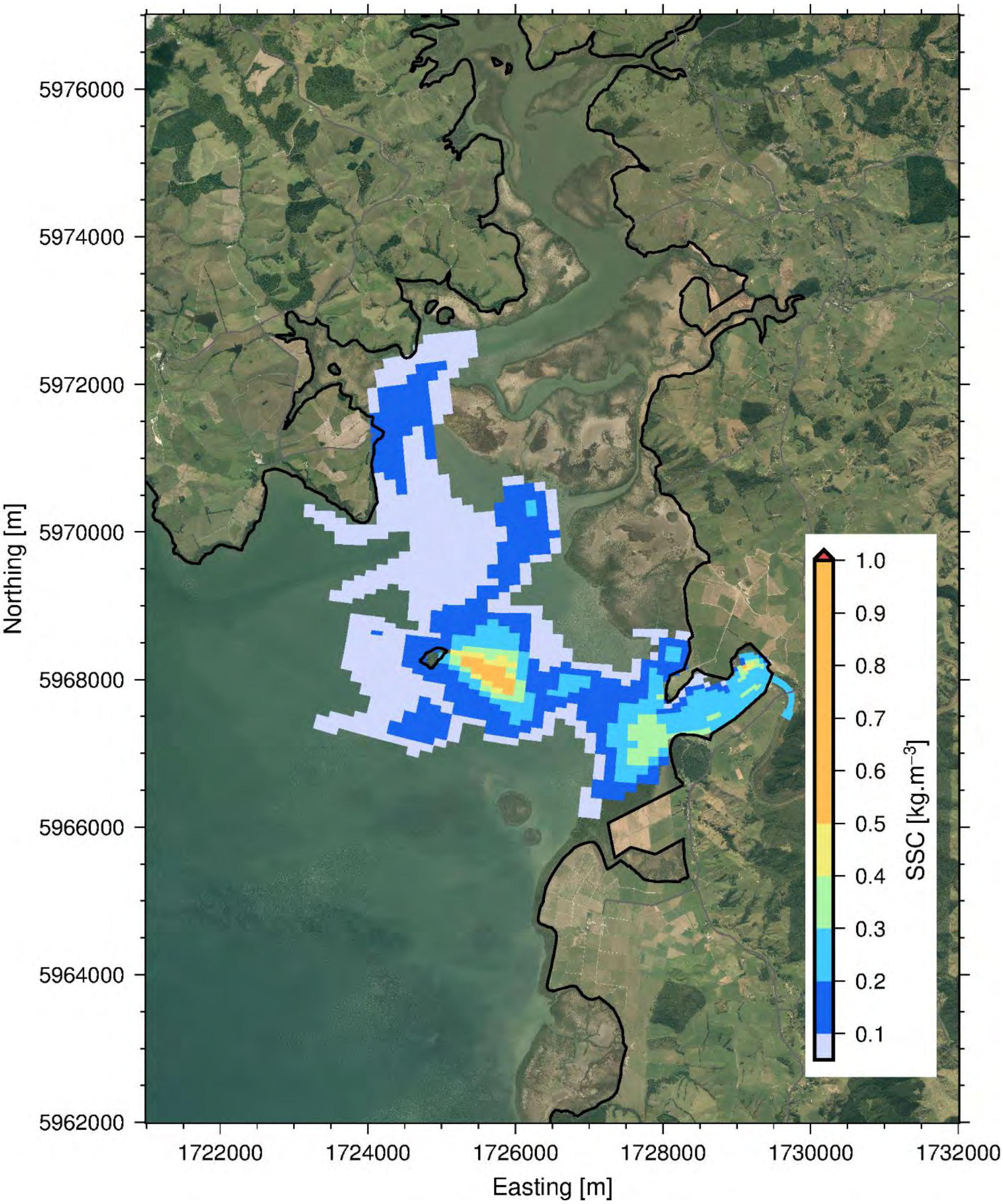

Figure 49: Suspended sediment concentration 1 day after the start of the event for the baseline 50-year ARI, calm wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

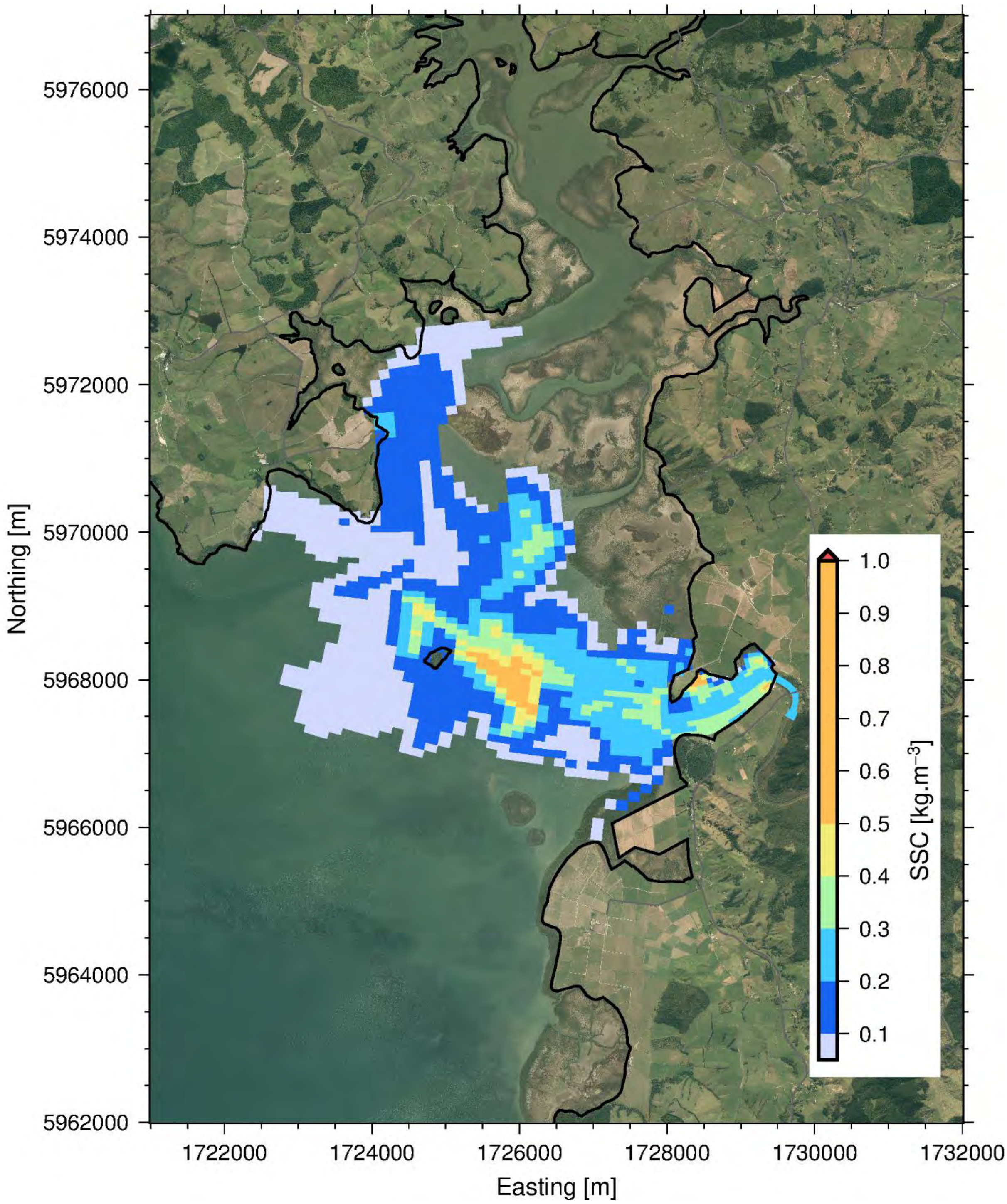

Figure 50: Suspended sediment concentration 1 day after the start of the event for the baseline 50-year ARI, SW wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

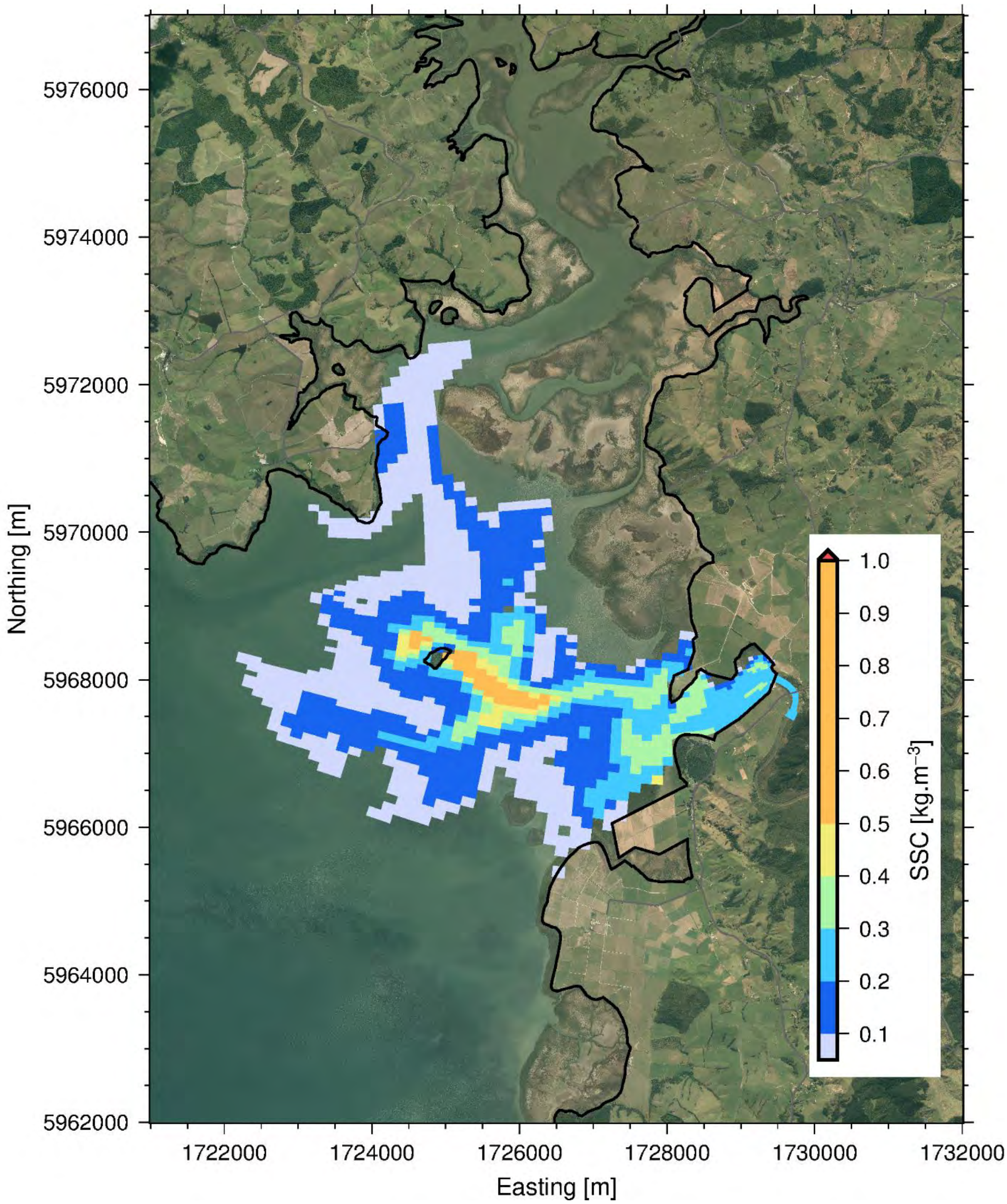

Figure 51: Suspended sediment concentration 1 day after the start of the event for the baseline 50-year ARI, NE wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

Suspended sediment concentration 3 days after the start of the event for the baseline 50-year ARI event

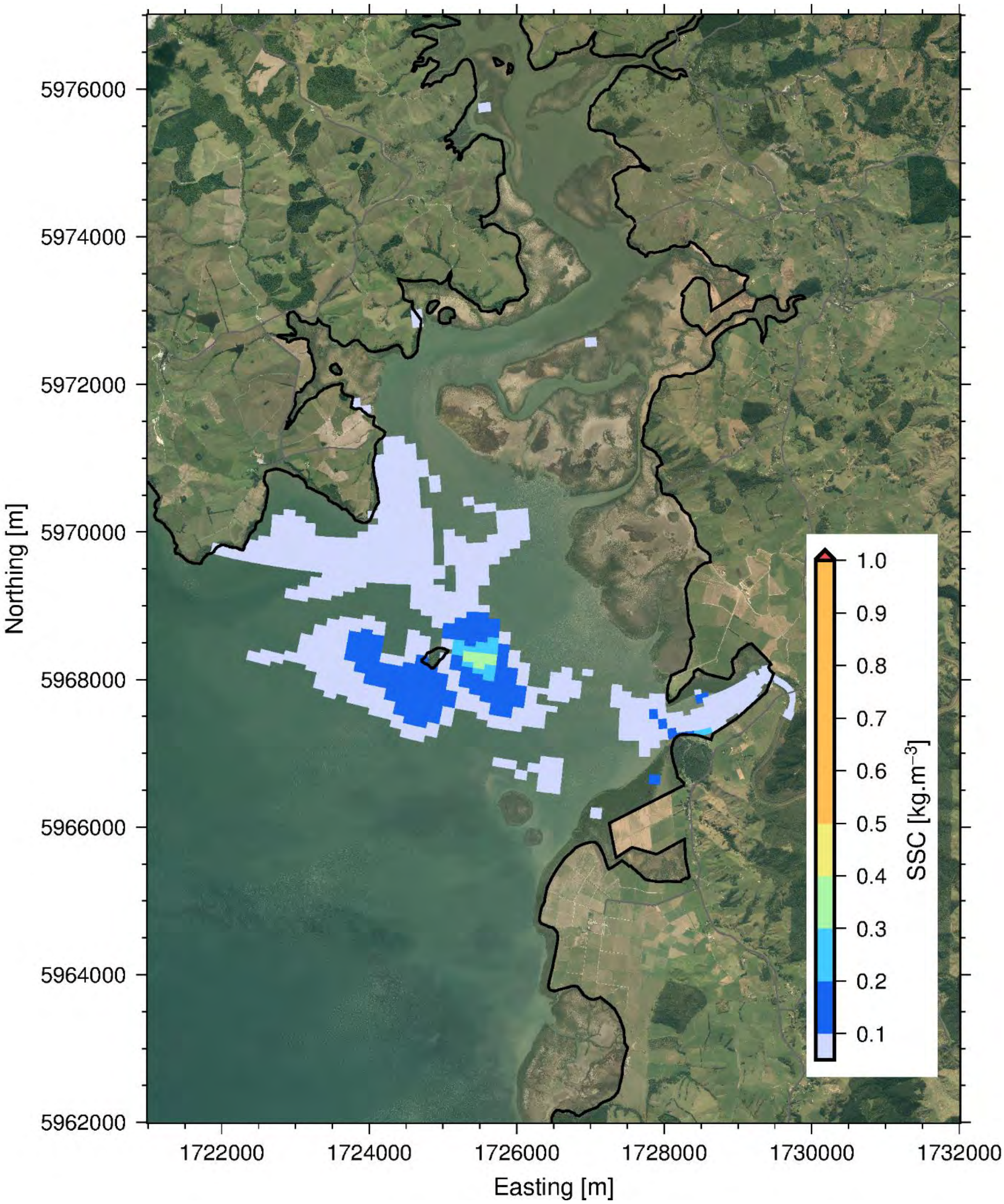

Figure 52: Suspended sediment concentration 3 days after the start of the event for the baseline 50-year ARI, calm wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

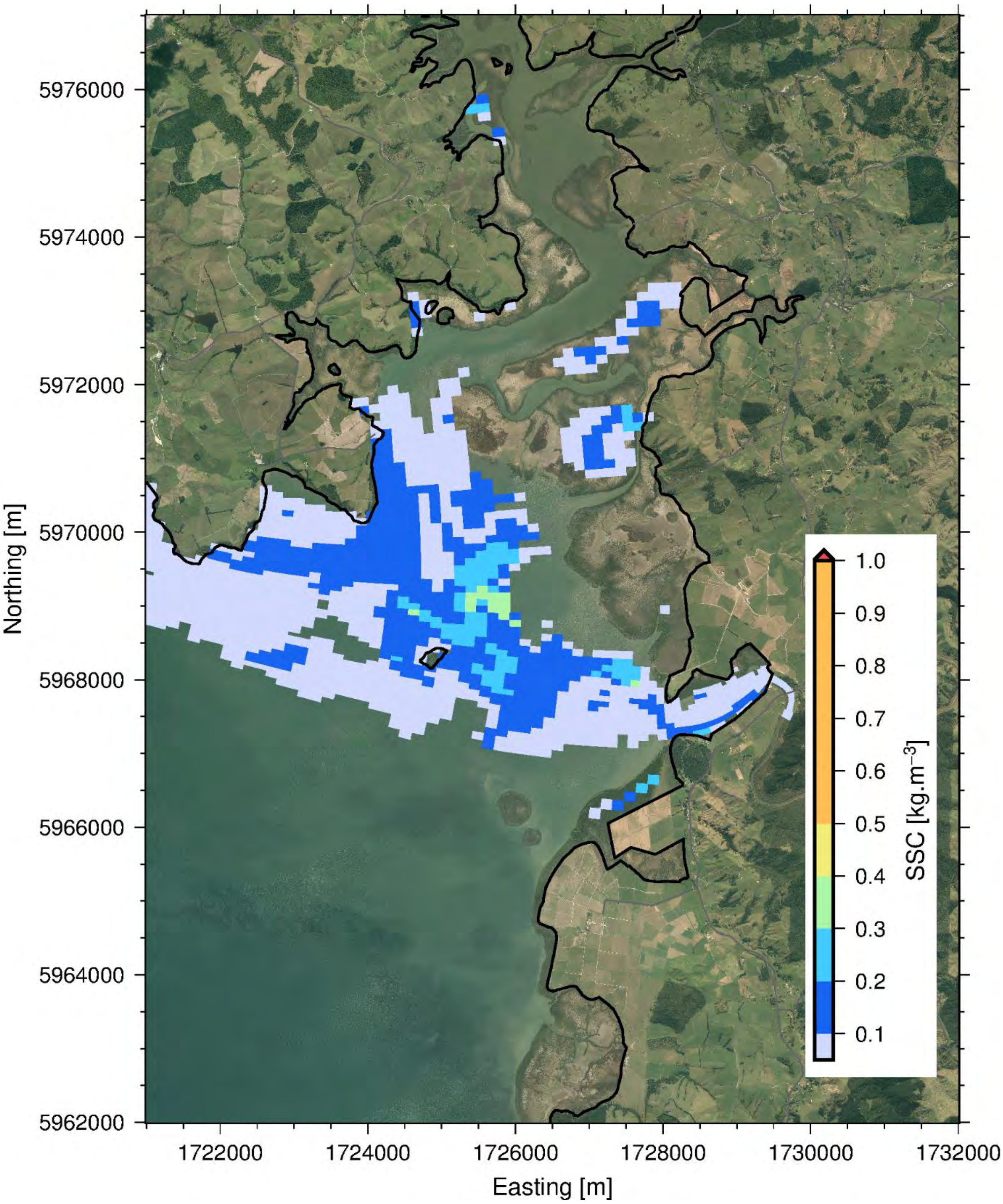

Figure 53: Suspended sediment concentration 3 days after the start of the event for the baseline 50-year ARI, SW wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

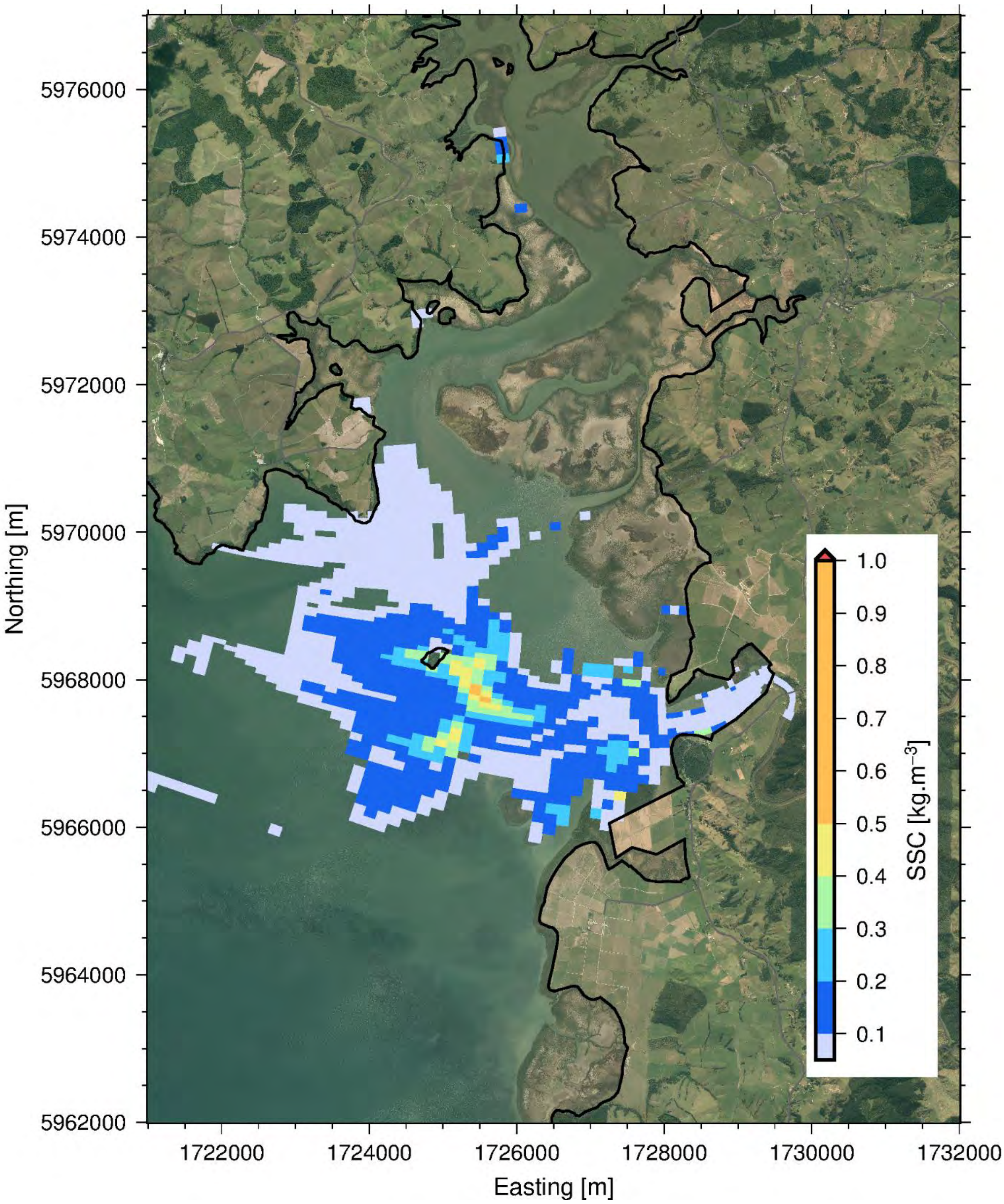

Figure 54: Suspended sediment concentration 3 days after the start of the event for the baseline 50-year ARI, NE wind event. Note the start of the event is when the suspended sediment concentration exceeds 0.01 kg/m^3 in the model input.

Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the baseline 10-year ARI event

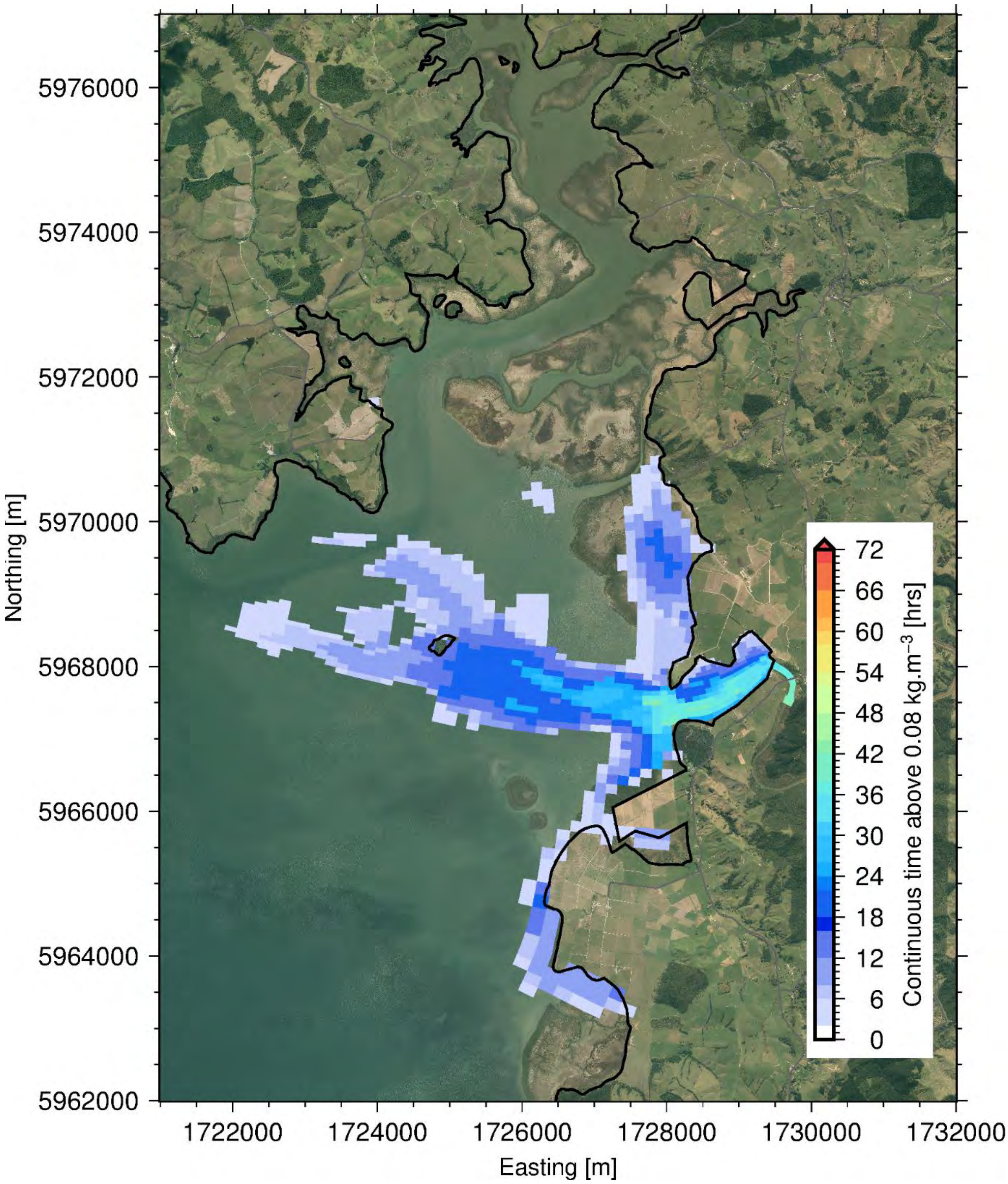

Figure 55: **Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the baseline 10-year ARI, calm wind event.**

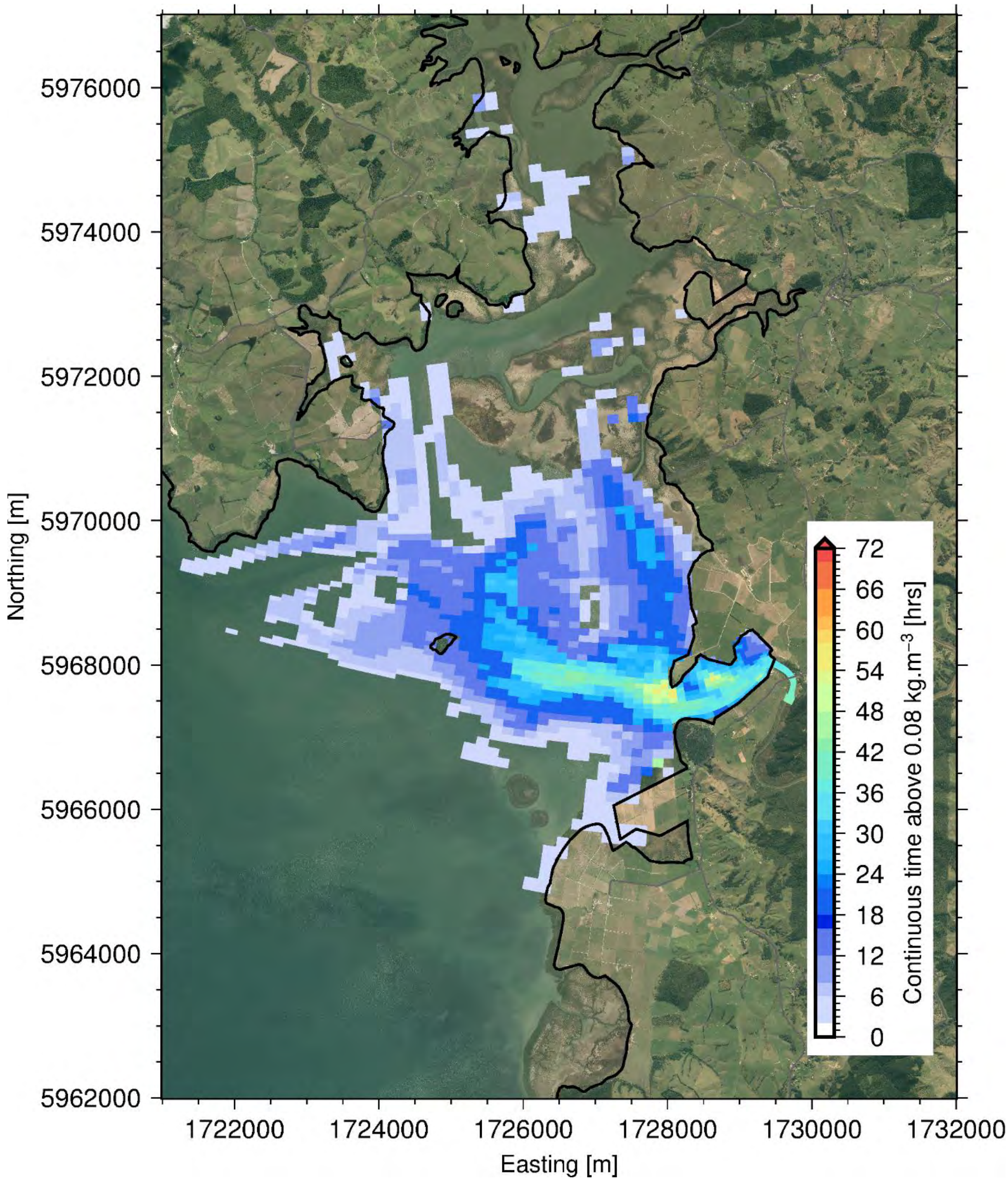

Figure 56: Maximum continuous time where the SSC exceeds 0.08 kg/m^3 for the baseline 10-year ARI, SW wind event.

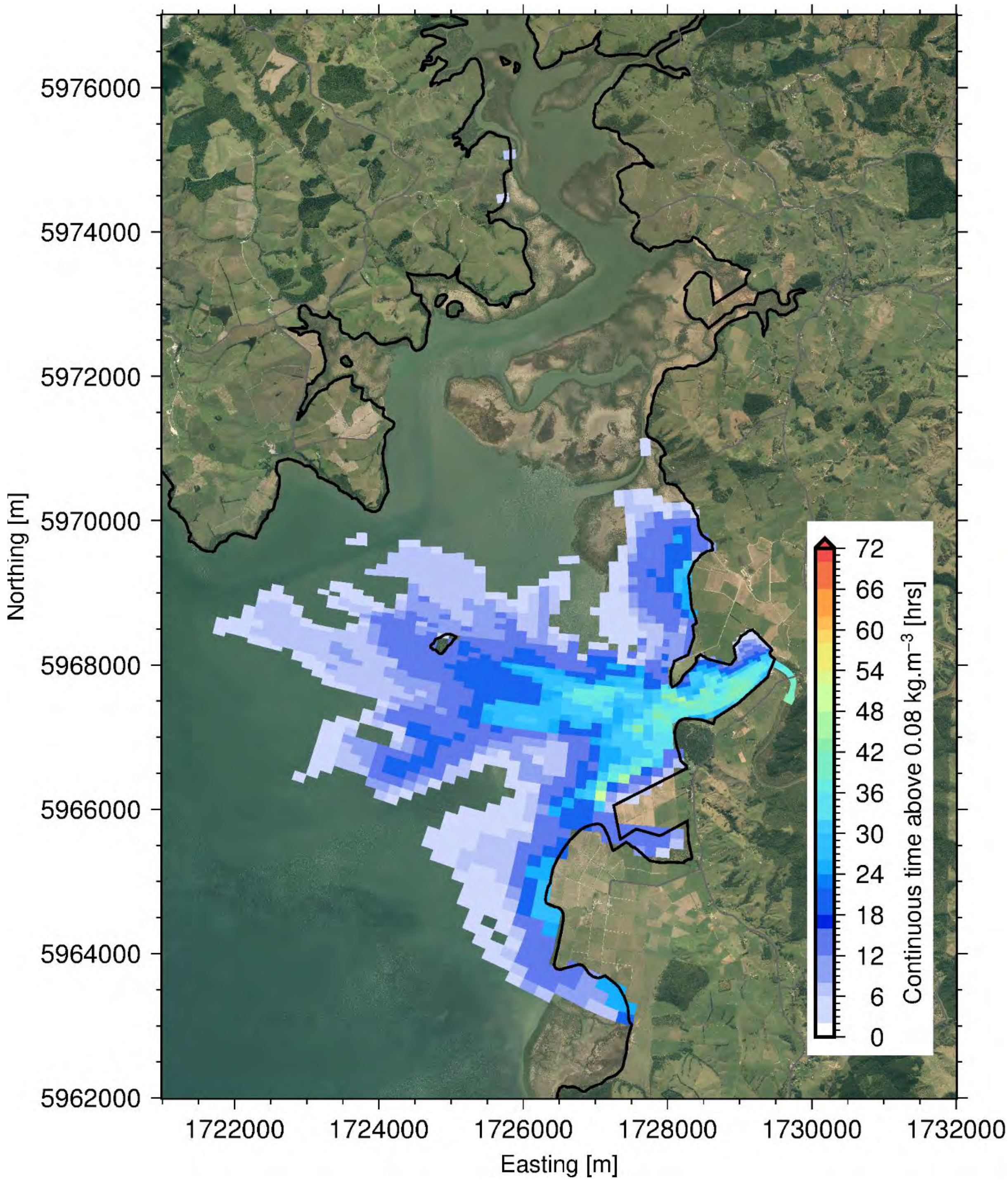

Figure 57: Maximum continuous time where the SSC exceeds 0.08 kg/m^3 for the baseline 10-year ARI, NE wind event.

Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the baseline 50-year ARI event

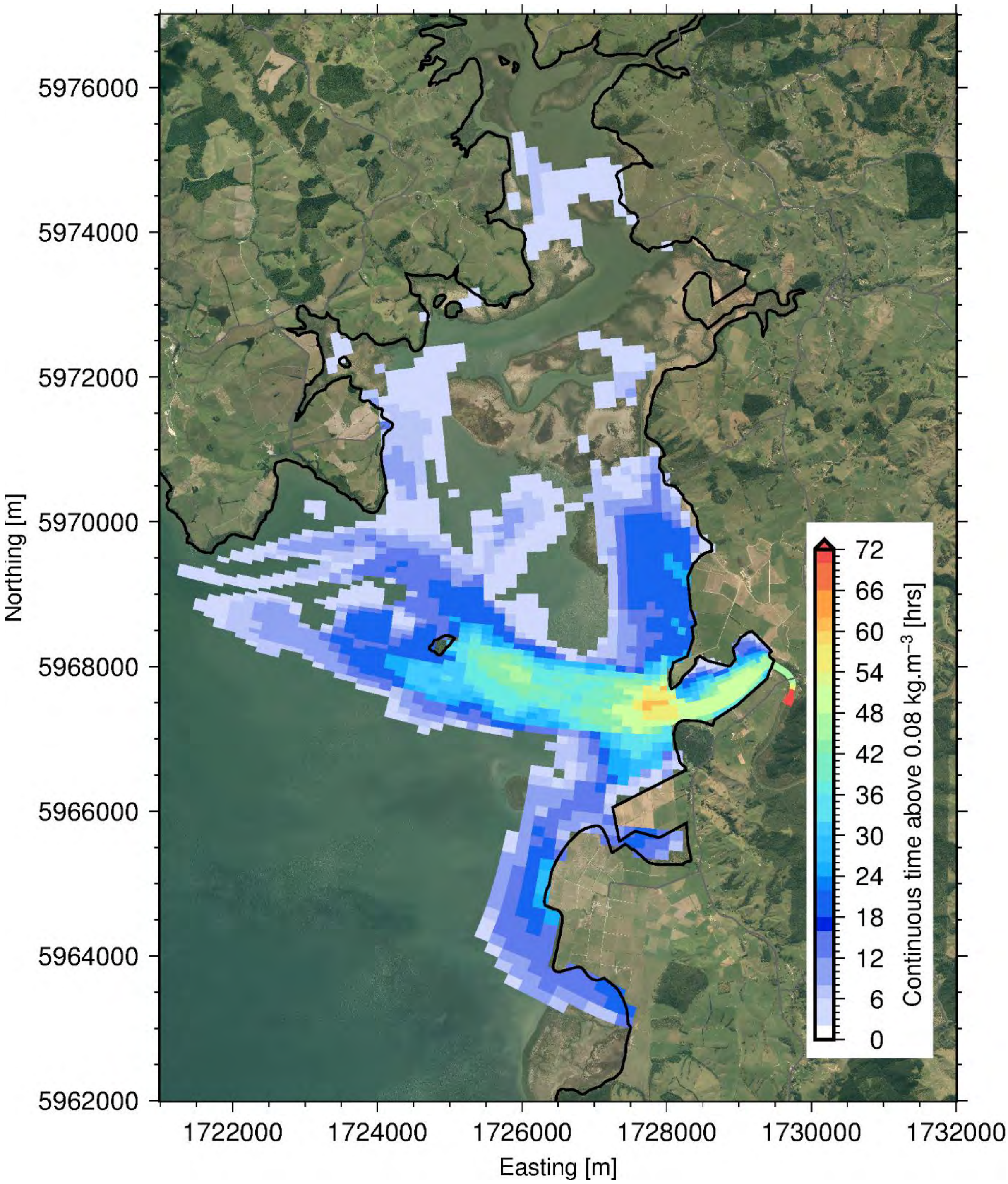

Figure 58: Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the baseline 50-year ARI, calm wind event.

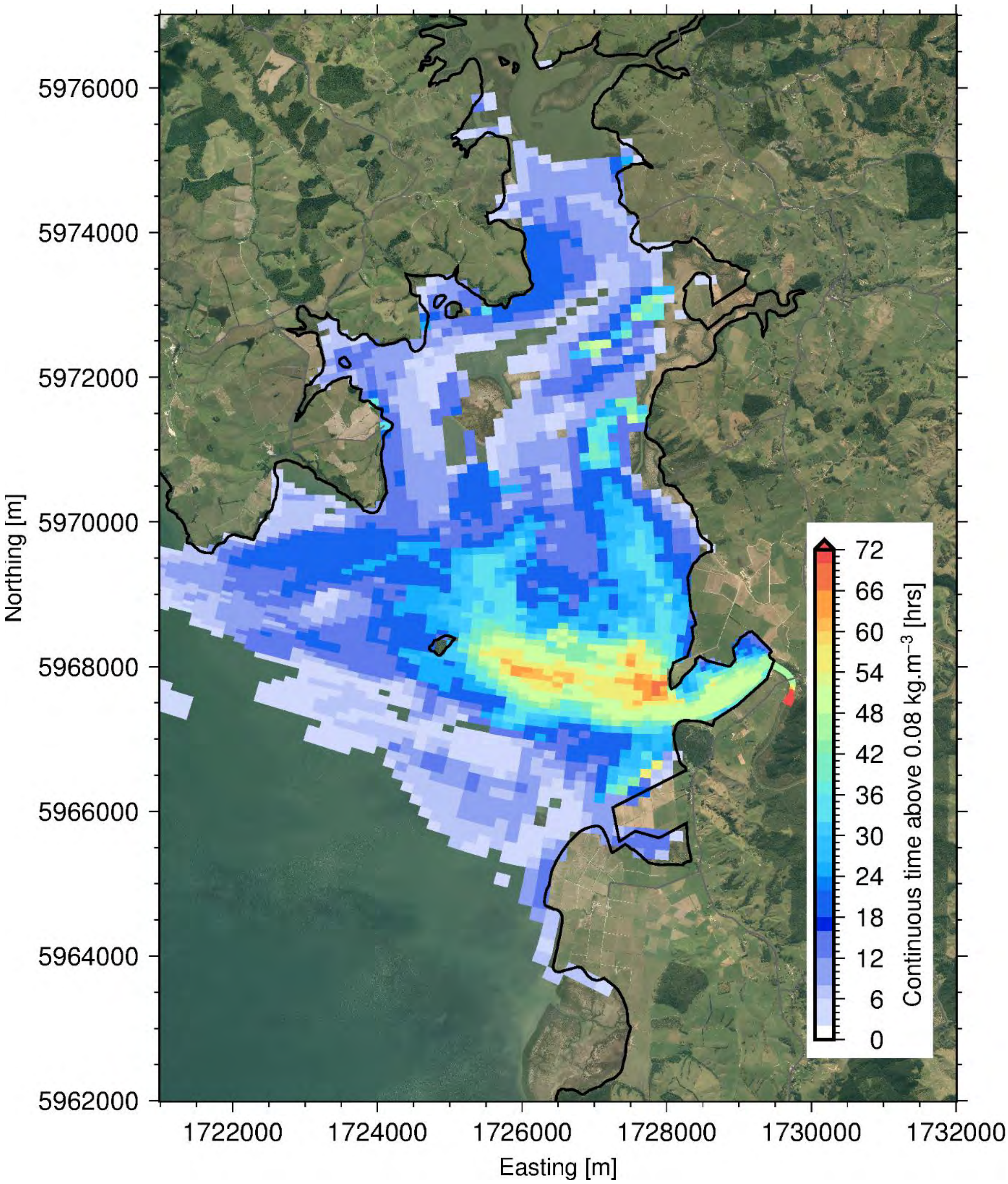

Figure 59: Maximum continuous time where the SSC exceeds 0.08 kg/m³ for the baseline 50-year ARI, SW wind event.

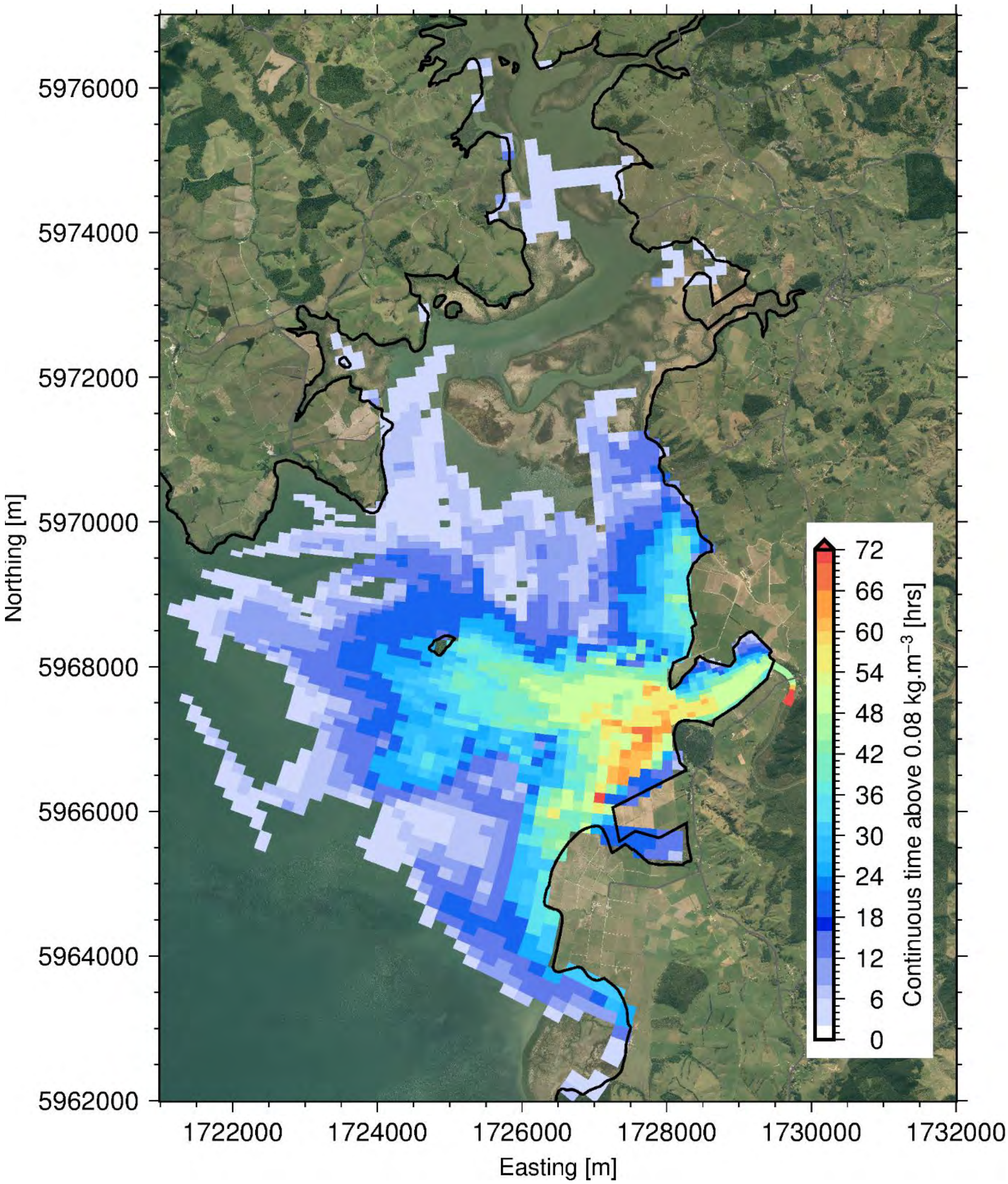

Figure 60: Maximum continuous time where the SSC exceeds 0.08 kg/m^3 for the baseline 50-year ARI, NE wind event.

Sediment deposition depth 3 days after the start of the event for the baseline 10-year ARI event

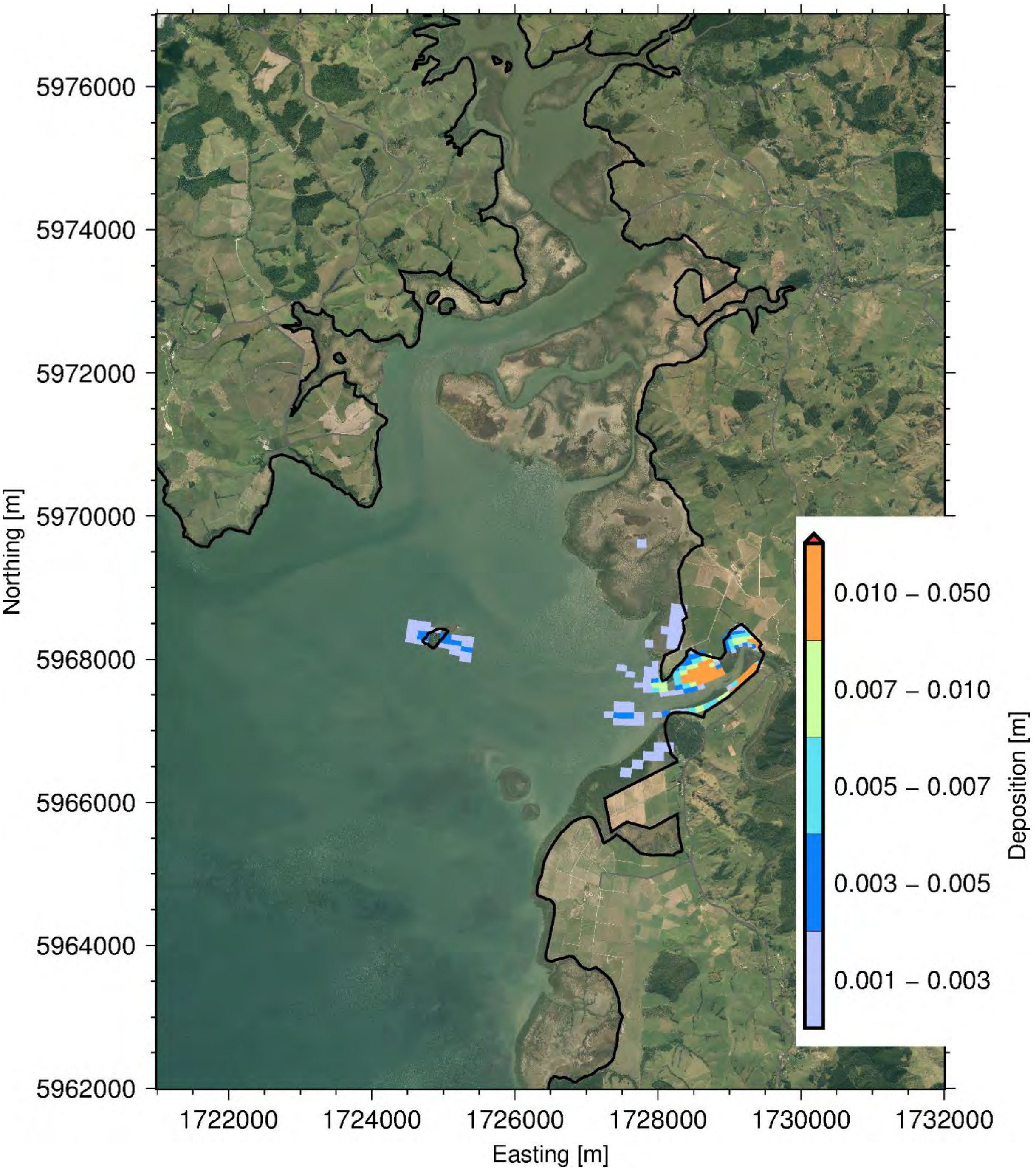

Figure 61: Sediment deposition depth 3 days after the start of the event for the baseline 10-year ARI, calm wind event.

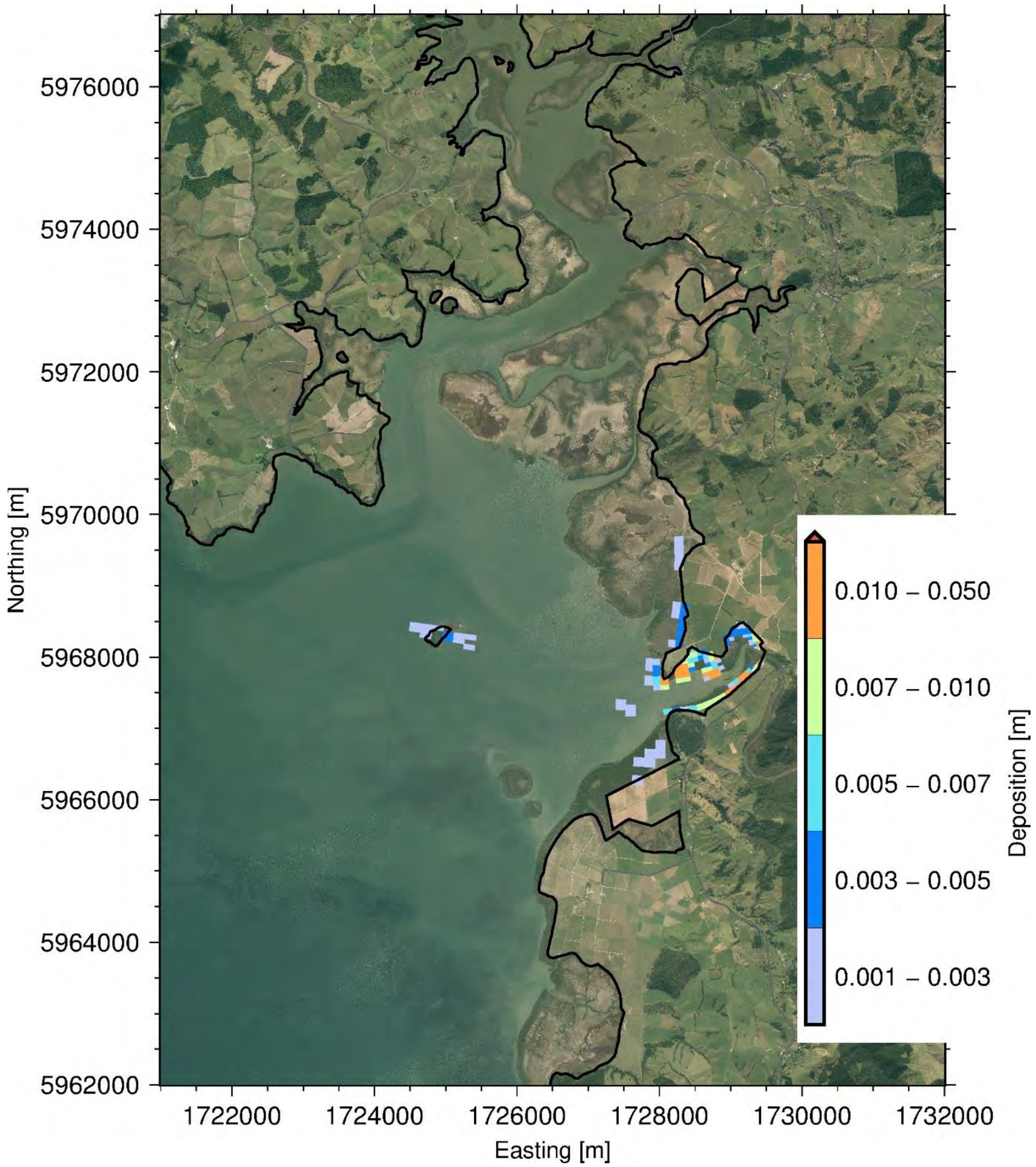

Figure 62: Sediment deposition depth 3 days after the start of the event for the baseline 10-year ARI, SW wind event.

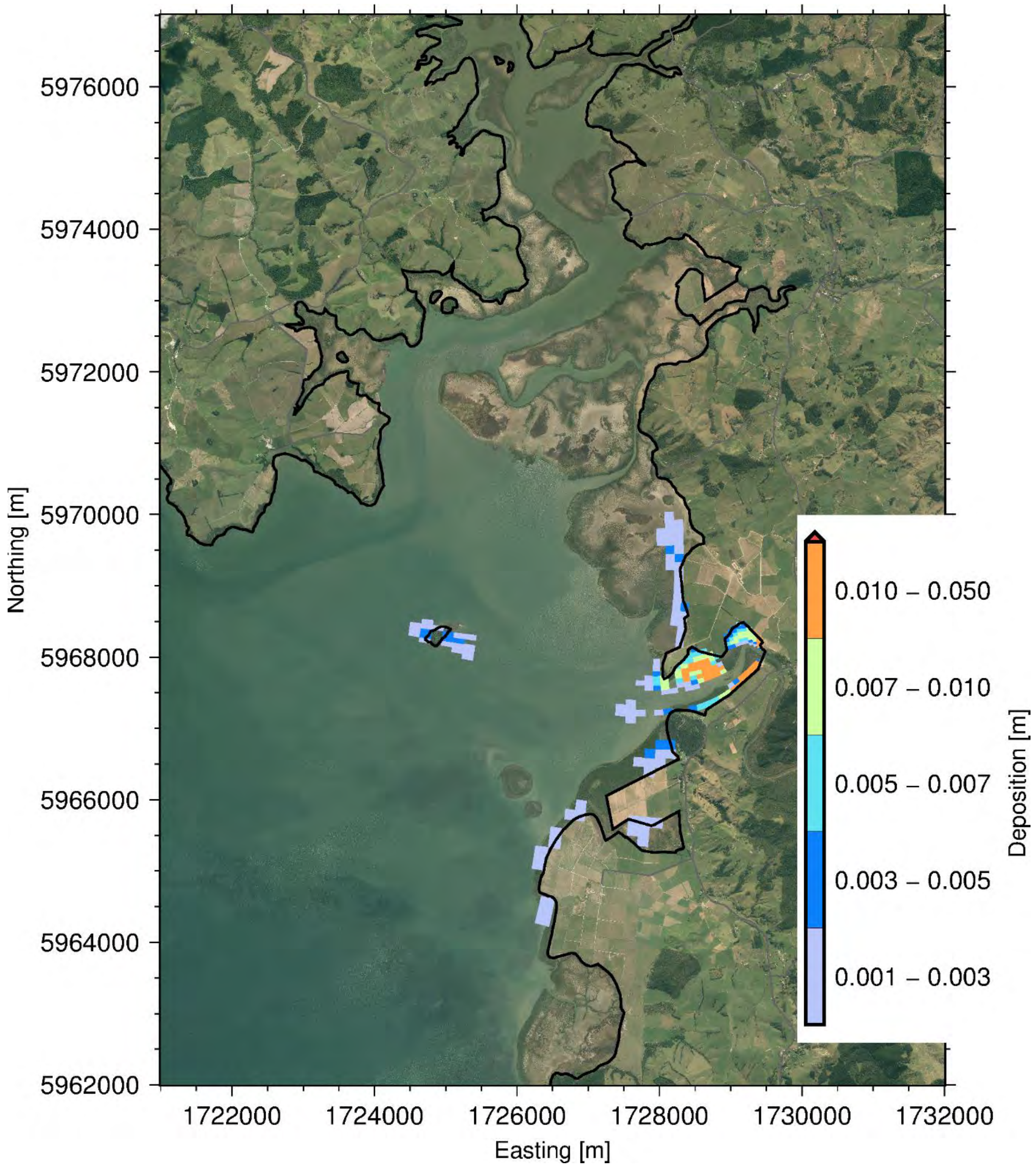

Figure 63: Sediment deposition depth 3 days after the start of the event for the baseline 10-year ARI, NE wind event.

Sediment deposition depth 3 days after the start of the event for the baseline 50-year ARI event

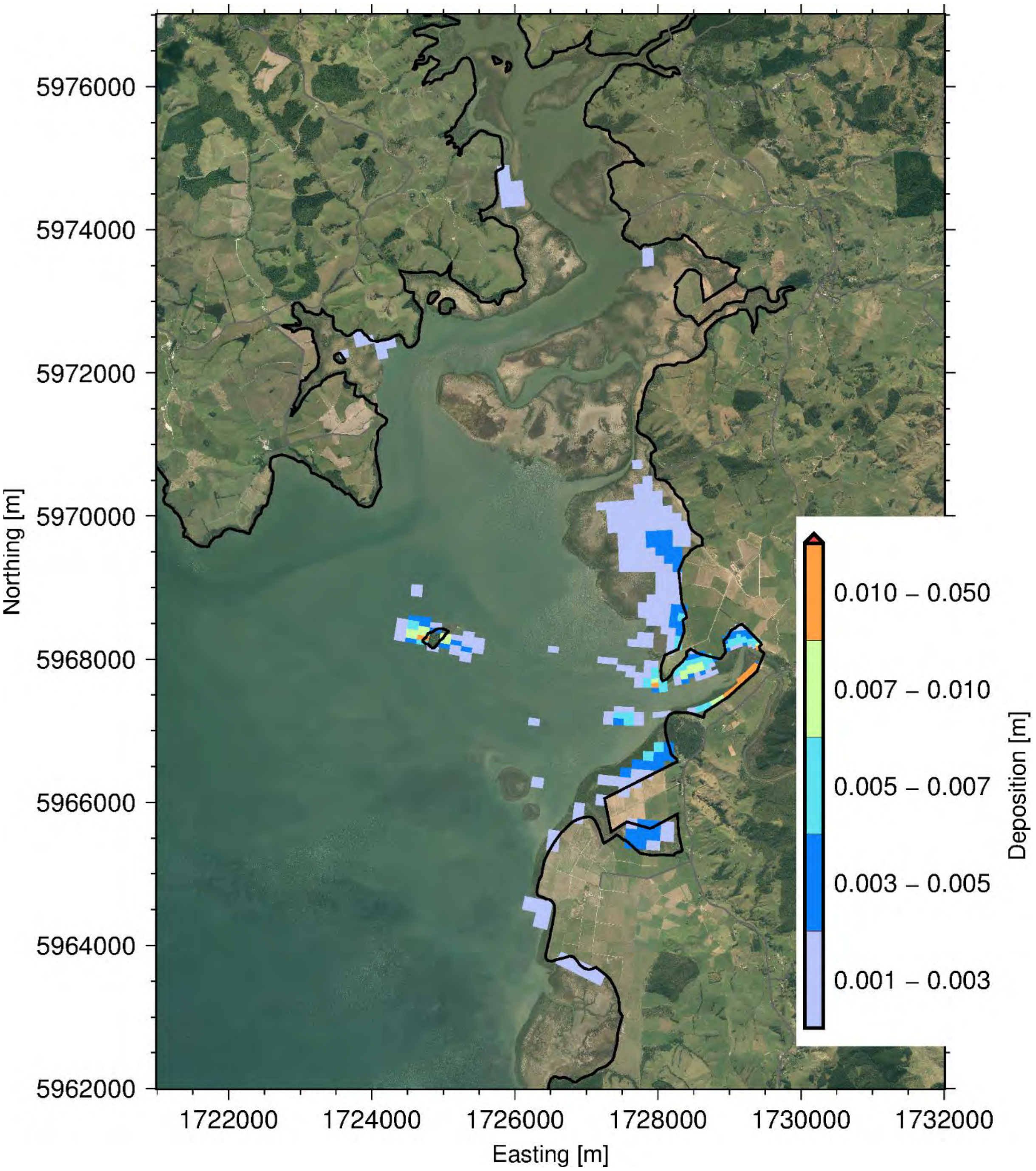

Figure 64: Sediment deposition depth 3 days after the start of the event for the baseline 50-year ARI, calm wind event.

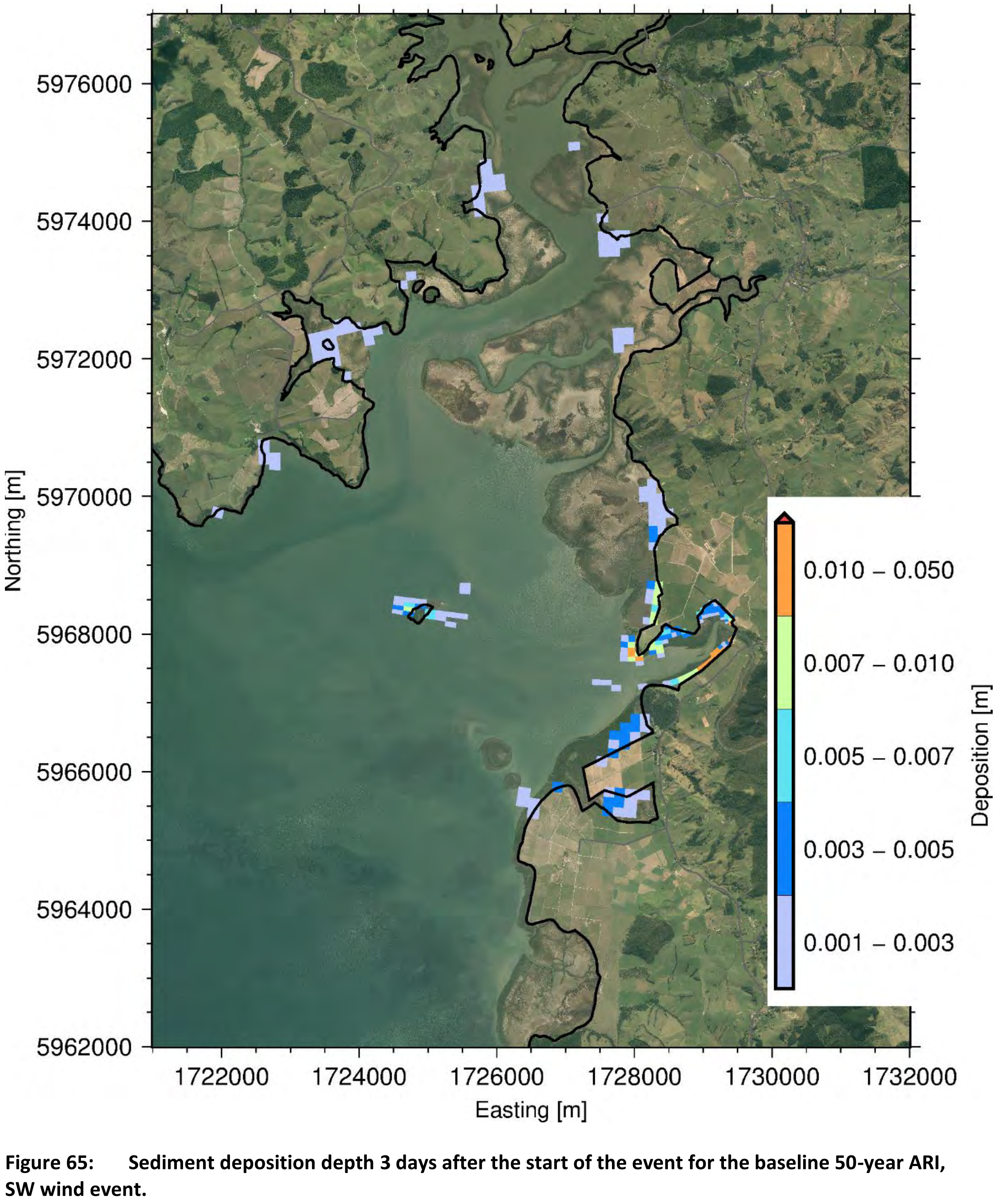

Figure 65: Sediment deposition depth 3 days after the start of the event for the baseline 50-year ARI, SW wind event.

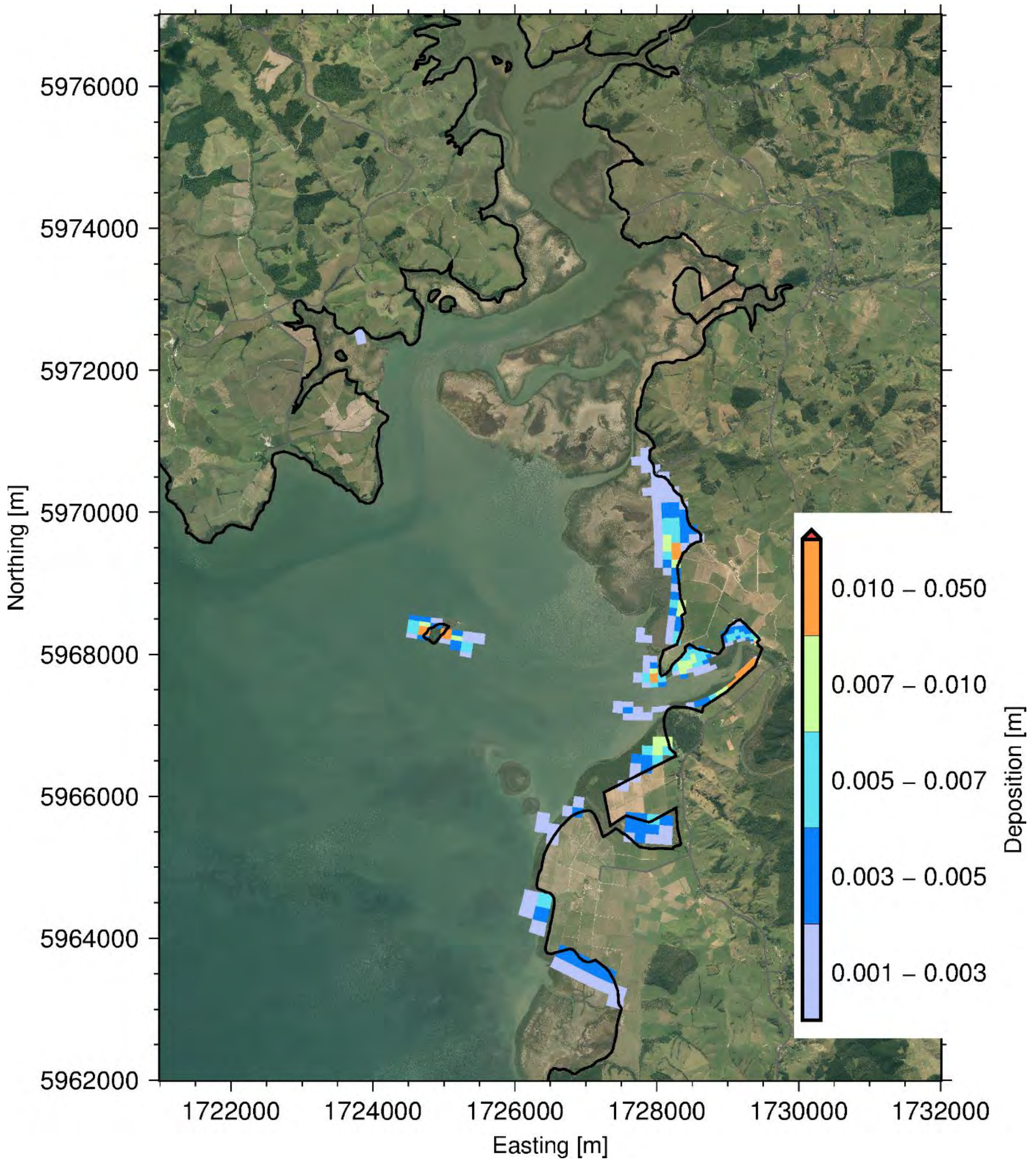

Figure 66: Sediment deposition depth 3 days after the start of the event for the baseline 50-year ARI, NE wind event.

Sediment deposition depth at the end of the 7-day simulation for the baseline 10-year ARI event

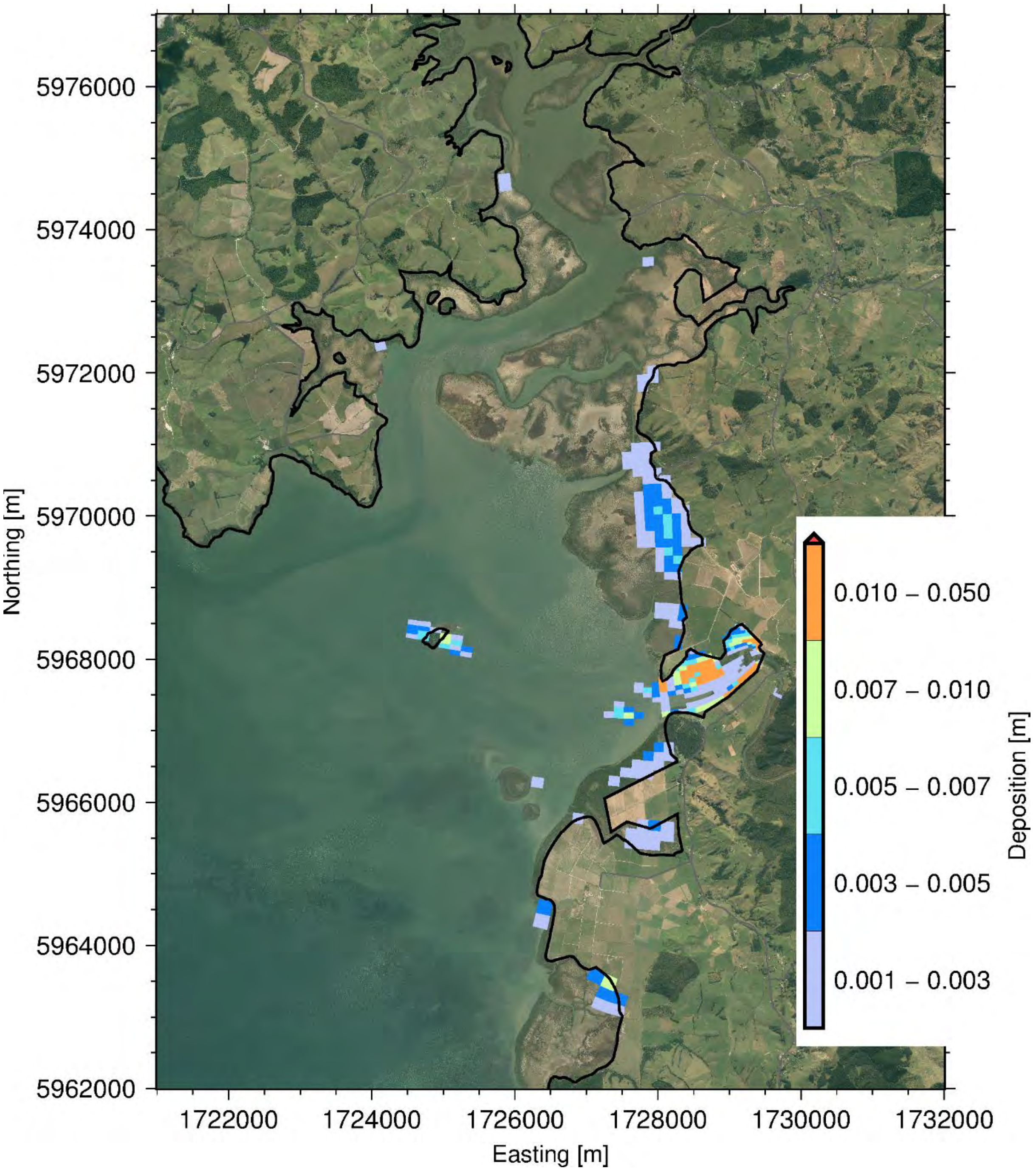

Figure 67: Sediment deposition depth at the end of the 7-day simulation for the baseline 10-year ARI, calm wind event.

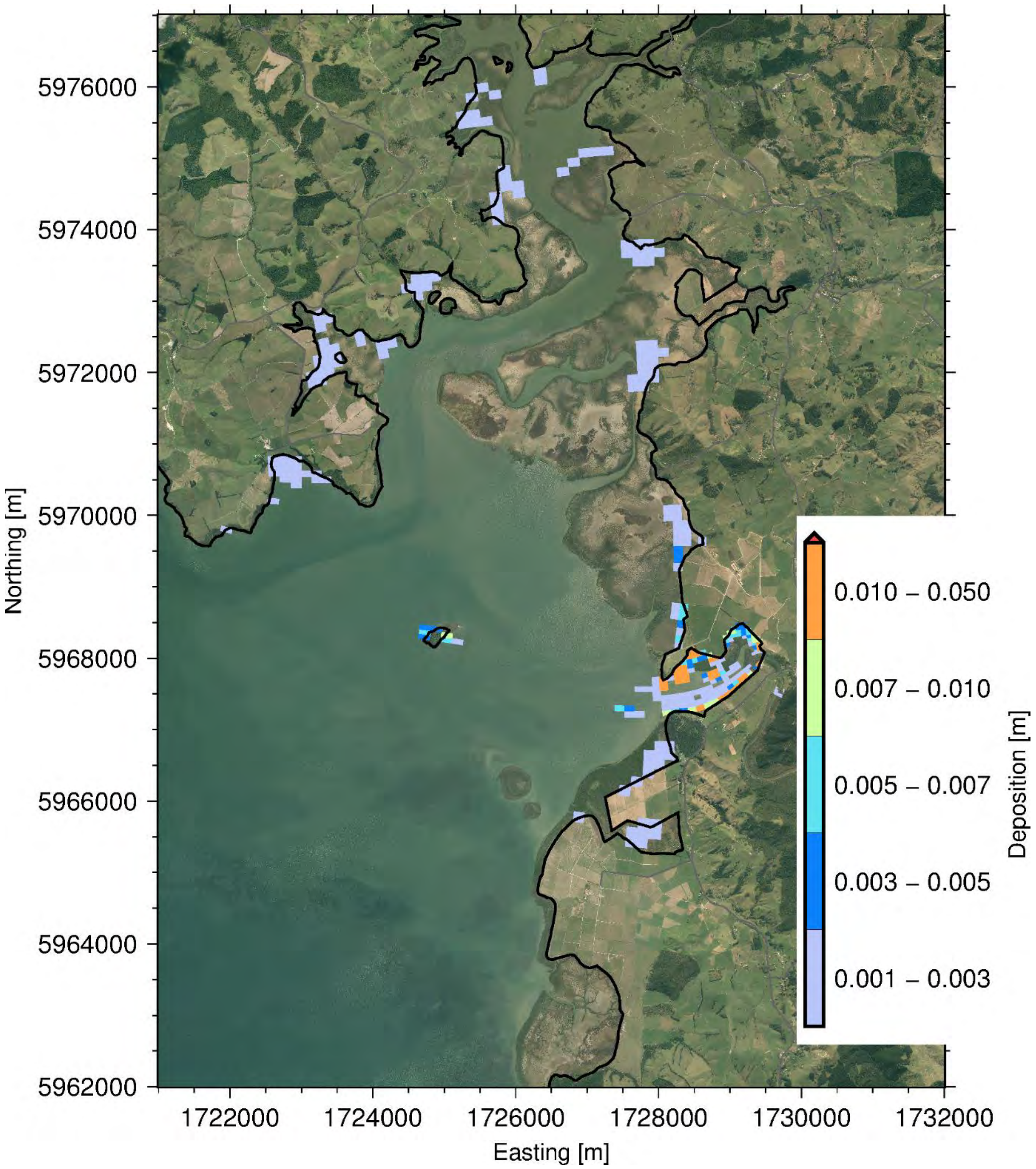

Figure 68: Sediment deposition depth at the end of the 7-day simulation for the baseline 10-year ARI, SW wind event.

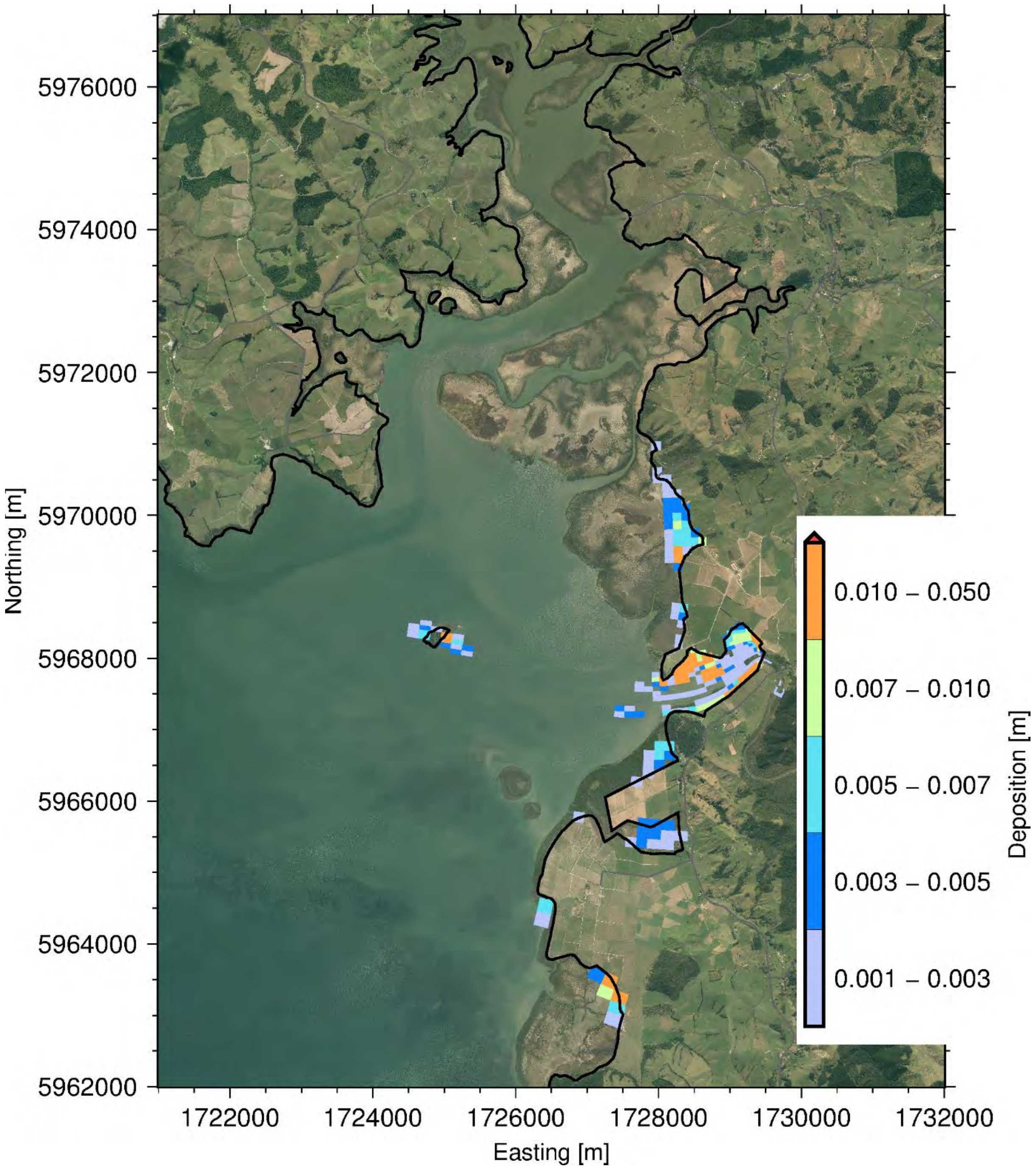

Figure 69: Sediment deposition depth at the end of the 7-day simulation for the baseline 10-year ARI, NE wind event.

Sediment deposition depth at the end of the 7-day simulation for the baseline 50-year ARI event

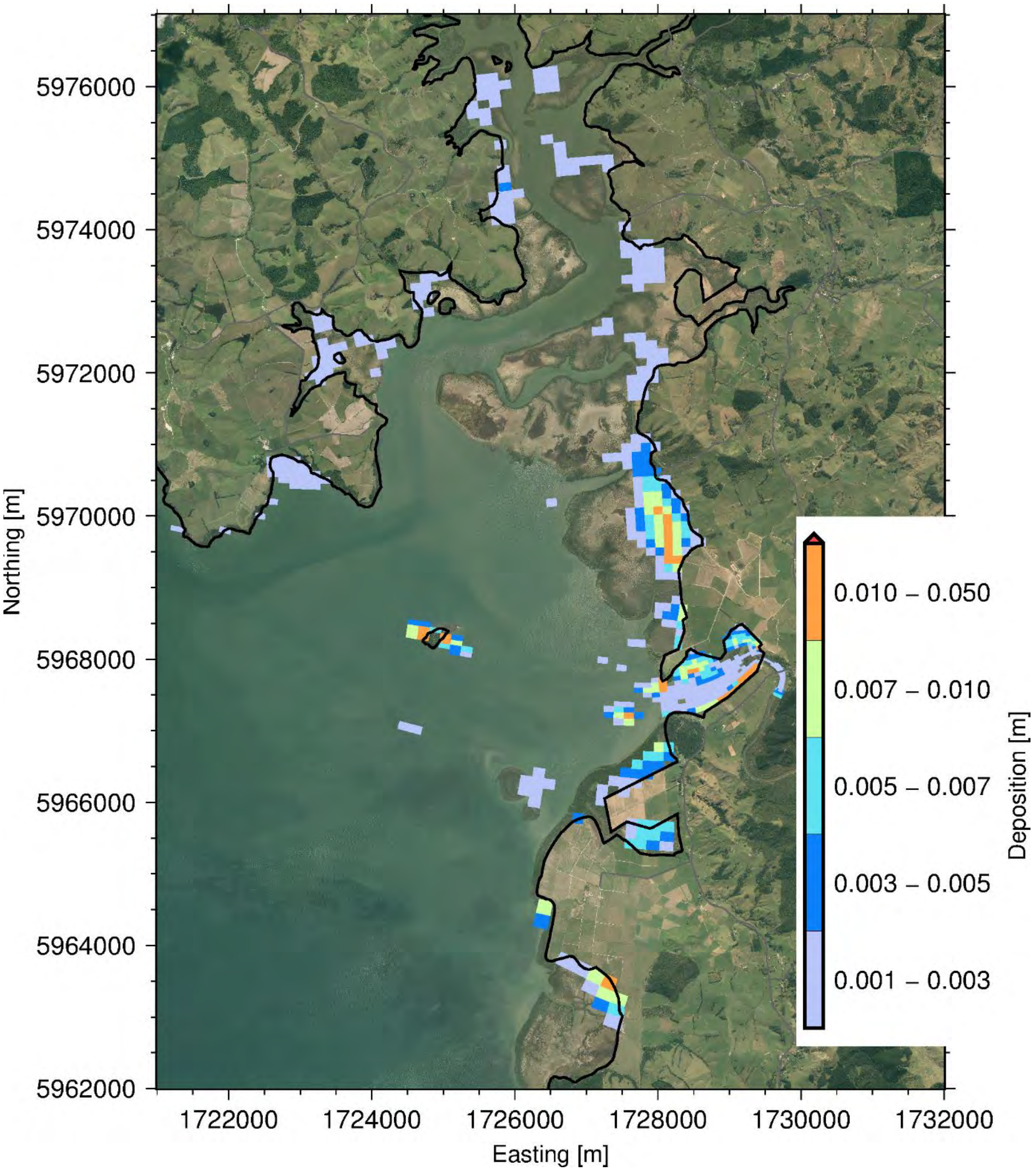

Figure 70: Sediment deposition depth at the end of the 7-day simulation for the baseline 50-year ARI, calm wind event.

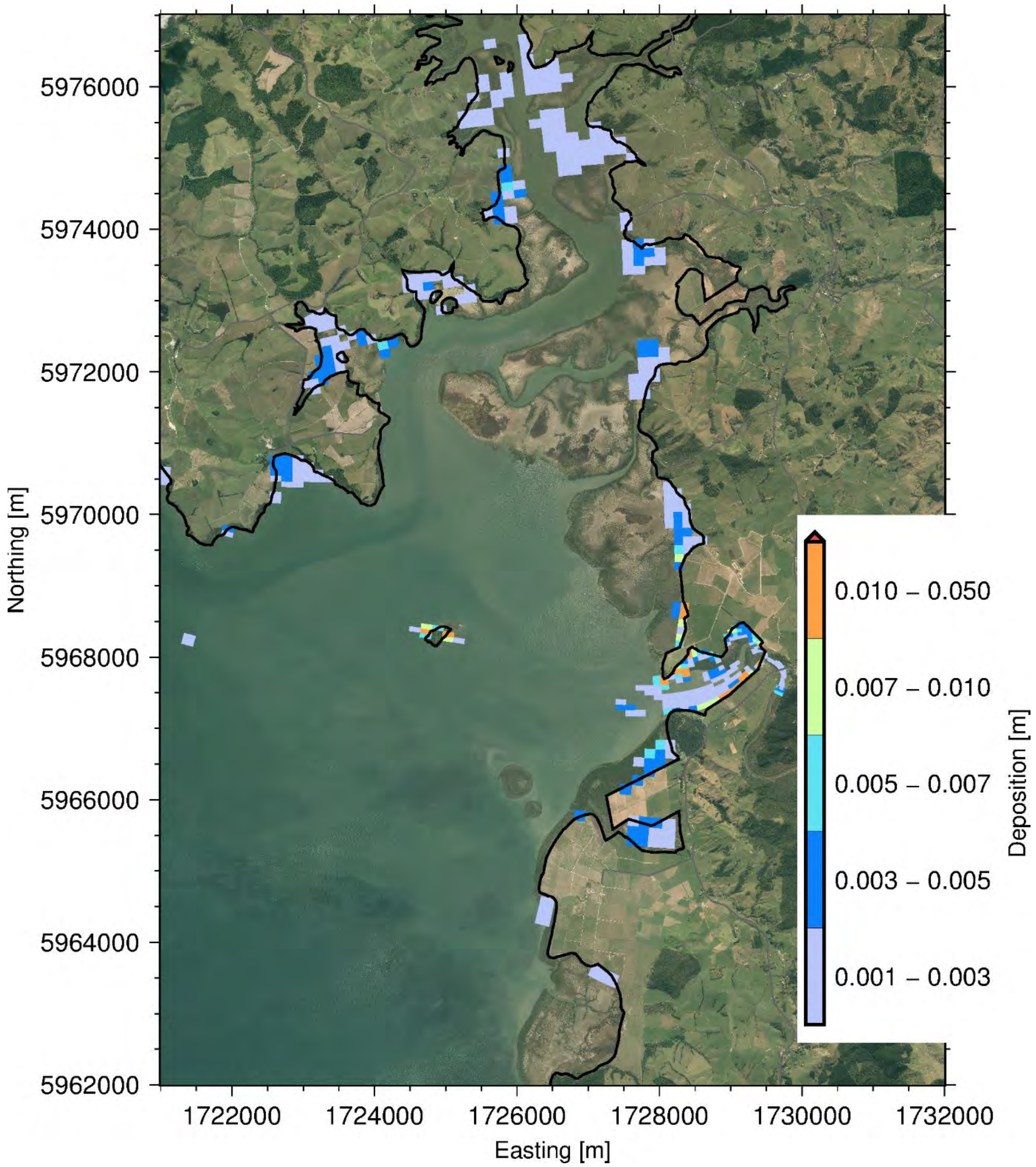

Figure 71: **Sediment deposition depth at the end of the 7-day simulation for the baseline 50-year ARI, SW wind event.**

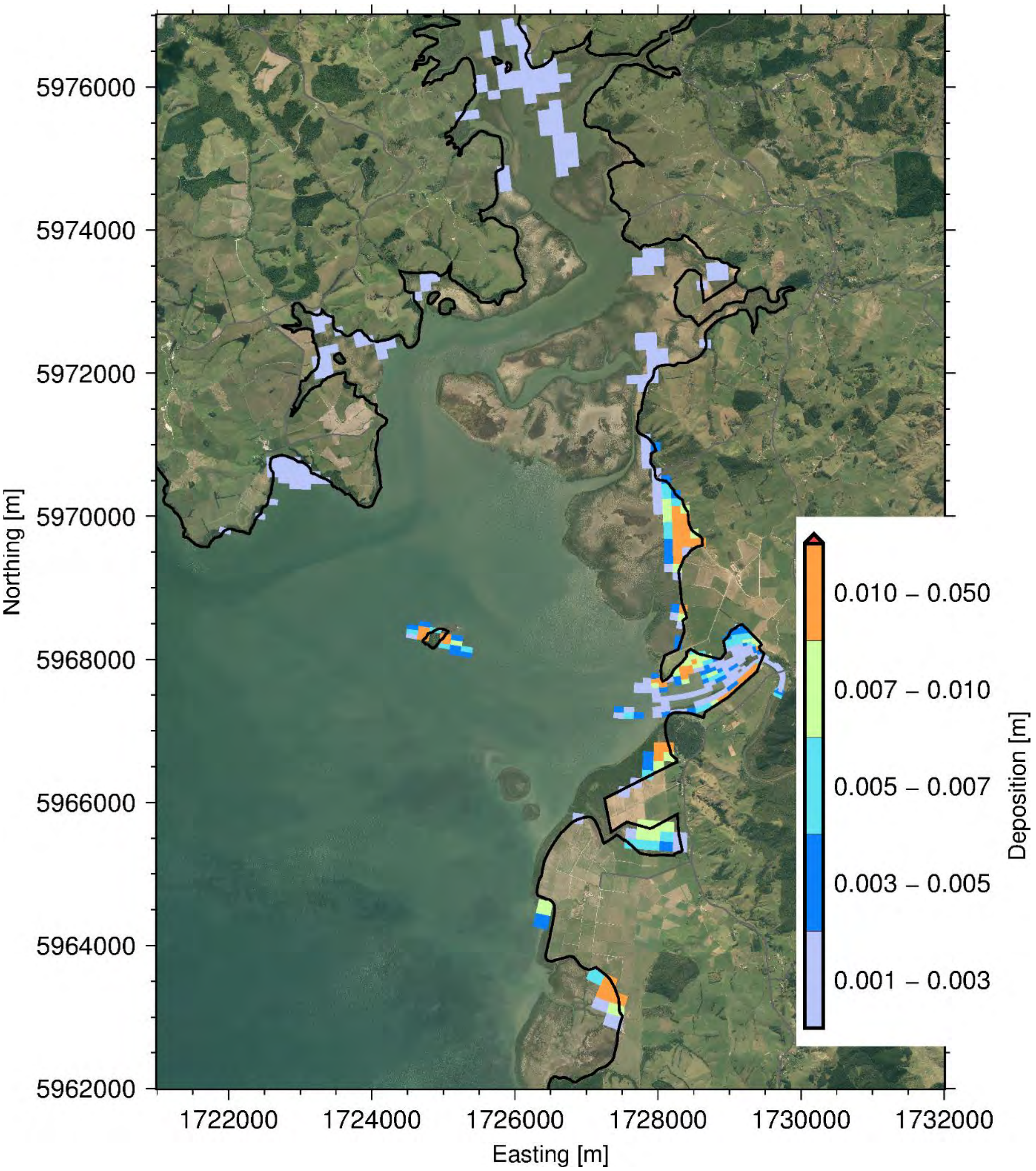

Figure 72: Sediment deposition depth at the end of the 7-day simulation for the baseline 50-year ARI, NE wind event.