Extent of seagrass in the Bay of Plenty in 2022

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Executive summary/ Whakarāpopototanga Matua

Seagrass (*Zostera muelleri*) were mapped in 2022 from aerial photography for estuaries in the Bay of Plenty and compared to historical distributions.

For the first time, we report on an increase in seagrass extent in Tauranga Harbour, following decades of declining seagrass health. Seagrass extents in Tauranga Harbour are 3740 ha, with 17.6 % (659 ha) of this being subtidal seagrass which has significantly returned and expanded in the harbour. The analysis of water quality data for Tauranga Harbour freshwater inflows shows that most streams have declining levels of total suspended solids. This indicates improvements in water clarity may be supporting the return and expansion of subtidal seagrass in Tauranga Harbour. On examining the current extent of seagrass against sediment mud content and current catchment sediment loads, it was evident that seagrass cover was higher in estuary sub-regions with lower sediment mud content and catchment loads. Where the sediment load retained in a sub-estuary reached over 1.5 $g/m^2/d$, the seagrass cover tended to decrease, as well as in sub-estuaries with muddy sediment covering more than 30% of the estuary.

In Ōhiwa Harbour, seagrass cover continues to show decreasing trends, with current coverage of 64 ha, representing a 53% loss since the earliest seagrass mapping in 1945. This latest decrease is along the margins of the seagrass beds closest to subtidal channels, indicating that sediment/light stress may be the cause of decline, causing a retreat into areas with less tidal submersion. Similarly, in Waihī Estuary, there are still declining trends in seagrass cover, with the current extent of 0.86 ha, equal to 1% of the earliest mapped coverage in 1943. In the Waioeka Estuary, Huntress Creek continues to show declines in seagrass cover, with the current extent of 0.19 ha, 5% of the historical extent in 1940.

In Maketū Estuary, the increase of freshwater flow from the Kaituna River has improved a number of estuarine health indicators in the estuary. Of note is reduced abundance of macroalgae, improving oxygen levels and reduced overall salinity which favours seagrass growth. We report here the return of numerous small patches of seagrass to the estuary, after its loss in 2019, however current cover is low (60 m^2) and limited to one location.

Contents

1 Introduction/Kupu Whakataki

Seagrasses are true flowering plants (Angiospermae) with stems, leaves, roots and flowers, which are specialised to grow rooted and submerged in estuarine and coastal environments (Turner & Schwarz 2006). In New Zealand there is one species of seagrass, *Zostera muelleri* (Jones et al. 2008), commonly referred to as eelgrass, karepō, nana and rimurehia. *Z. muelleri* is a native species with a national threat status of 'at risk-declining' according to the New Zealand's Threat Level Classification System, managed by the Department of Conservation (de Lange *et al*. 2018). Seagrass meadows are an important component of the estuarine ecosystem, providing ecosystem services including habitat, food, and nursery areas for a range of fish and macroinvertebrates, which increases biodiversity (Morrison et al., 2014). Seagrasses also trap sediments and stabilise the seafloor, remove nutrients (contributing to nutrient cycling), whilst providing a carbon sink removing CO_2 and sequestering carbon within their sediments (Unsworth *et al*., 2019).

With systematic broad-scale mapping of seagrass extents from aerial photography extending back to the mid-20th century, significant losses of seagrass beds have been identified throughout New Zealand (Park 1999, Inglis 2003, Ha et al., 2021). The direct causes of such changes have not been determined and may vary in different locations, but are likely to involve compounding impacts of sedimentation following the conversion of land from native forest to agricultural and urban land use (Morrison *et al*. 2014, Our Marine Environment 2022), sediment nutrient enrichment, reduced light availability, marine heat waves and physical disturbance (e.g., loss from land reclamation, dredging, anchoring and moorings), waterfowl grazing and disease (Orth et al., 2006, Roca *et al*., 2016, Unsworth *et al.*, 2019, Zabarte-Maetzu *et al*., 2021c). For a detailed summary of stressors to seagrass in the Bay of Plenty, please refer to Crawshaw *et al.* 2023.

The purpose of this report is to provide mapping of seagrass extents in the Bay of Plenty and an assessment of trends and changes over time. In addition, we explore the factors which may be contributing to changes in seagrass cover over time by examination of environmental variables that are frequently associated with seagrass health, including substrate quality, and influx of water-borne nutrients and suspended sediments.

1.1 Estuaries of the Bay of Plenty

The Bay of Plenty is located on the northeast coast of the North Island, New Zealand and has 258 km of exposed coastline stretching from Waihī in the northwest of the region to Lottin Point in the east. There are a number of coastal inlets and nearly all can be classed as estuaries. Larger inlets tend to be barrier enclosed estuaries while there are a number of smaller river mouth estuaries.

For estuarine systems that contain seagrass, there are two main harbours (Tauranga and Ōhiwa) and two major estuaries (Maketū, Waihī), and one smaller riverine estuary (Waioeka) (Figure 1). There is an additional estuary (Waiōtahe), that had just 2 m^2-3 m^2 of seagrass in the 1990's, which had disappeared by 2015 and will not be reported here.

Figure 1 *Major harbours (Tauranga and Ōhiwa) and estuaries (Maketū, Waihī, Waioeka) (blue) in the Bay of Plenty that contain seagrass habitats. Photo credit: PhotoOblique.*

1.1.1 Tauranga Harbour

Tauranga Harbour has two major basins (north and south) being largely separated by a shallow intertidal area in the middle with each basin having its own entrance to the open sea. These two basins have been assessed to be hydrodynamically distinct. Tauranga Harbour is categorised as a shallow intertidal dominated estuary (SIDE). Its estuary characteristics and catchment size and land use are provided in Tables 1 and 2. The catchment is dominated by steep to rolling land and the geology is dominated by volcanic soils (85%). Overall, the harbour is in a moderate ETI eutrophic state (B) with the mud grade (C) indicating a high level of environmental stress from sediment inflows. There is however considerable variation in environmental state over this large harbour with many of the sheltered sub-estuaries showing a far poorer grading. Detailed assessments of sub-estuary environmental state can be found in Crawshaw *et al.* (2022).

1.1.2 Ōhiwa Harbour

Ōhiwa Harbour is a moderately sized, shallow, spit enclosed drowned valley system classed as a SIDE. Its general estuary and catchment land use characteristics are provided in Table 1 and 2. The catchment geology and soils are largely non-volcanic sedimentary material with the terrain dominated by steep, erodible land. The harbour has an overall ETI eutrophic grade of B and a mud grade of D, indicating significant stress from sedimentation. A more detailed assessment of environmental sate can be found in Park (2020).

1.1.3 Maketū Estuary

Maketū Estuary is a smaller shallow inlet classed as a SIDE. It had historically been the outlet of the Kaituna River which was diverted from the estuary in 1954 and more recently partially returned. These major hydrological changes in combination with extensive loss of associated wetlands has caused significant ecological impacts and changes. Estuary and catchment characteristics are provided in Tables 1 and 2. This catchment is dominated by volcanic geology and porous ash or pumice soils everywhere except the lower plains, which are made up of organic or gley soils. The estuary has an NZ ETI trophic grade of C indicating a high state of eutrophication reflected in part by extensive macroalgal blooms in the late 90's to 2020. The estuary also has a poor Mud grade of D, indicating significant stress from sedimentation. More detailed environment assessment is provided by Park (2018).

1.1.4 Waihī Estuary

Waihī Estuary is a small shallow inlet classed as a SIDE which has had extensive loss of associated wetlands. Characteristics of the estuary and catchment are provided in Tables 1 and 2. The geology in this catchment is dominated by volcanic material, with some peats and sands in the lowland drained wetland areas. The estuary has an estuarine trophic index (ETI) grade of C, indicating a state of high eutrophication and a Mud grade of D indicating significant stress from sediment inflows. Nitrogen loads into the estuary have been increasing over time and are linked to the extensive macroalgal blooms that have occurred over the last decade. A more detailed assessment of environmental state is provided by Park (2018).

1.1.5 Waioeka Estuary

Waioeka Estuary is a small "Shallow, Short Residence Time Tidal River Estuary" (SSRTRE) which are characterised by high river flushing. Other aspects of the estuary and catchment land use are provided in Tables 1 and 2. The geology and soils of the catchment are non-volcanic, and terrain is dominated by steep hilly Raukumara Range with Ōpōtiki area being low land/coastal plains. The estuary has an estuarine trophic index (ETI) grade of B and a mud grade of D (Park 2020).

Table 1 Physical characteristics and NZ ETI grading for the overall eutrophic state and "Mud" grade of each estuary.

Estuary	Area Km^2	Volume m^3	% intertidal	Eutrophic	Mud grade
Tauranga	210.0	425,300,509	77	B	C
Ohiwa	26.4	44,190,150	83	B	D
Maketu	2.36	3,548,528	80	C	D
Waihi	3.34	4,353,159	57	C	D
Waioeka	1.3	3,093,189	14	B	D

Table 2 Catchment size and percentage land use cover in native forest, exotic forest, dairy, dry stock, horticulture (includes lifestyle blocks) and urban area categories.

	Catchment size (km^2)	Native %	Exotic %	Dairy %	Dry stock %	Horticulture %	Urban %
Tauranga	210.0	35	9	10	11	22	9
Ōhiwa	18.7	29	19	28	12	5	0.5
Maketū	60.0	26	20	20	17	9	3
Waihī	35.8	12	19	40	16	13	0.2
Waioeka	123.3	80	4	5	6	3	2

2 Methodology/Huarahi

2.1 Seagrass cover mapping

Seagrass mapping for the Bay of Plenty region has been undertaken at regular intervals following the availability of suitable high-quality aerial imagery. The latest mapping used aerial photography from 2022 which was supplied as 10 cm pixel resolution (0.1 m GSD), 3-band (RGB) uncompressed GeoTIFF. The final spatial accuracy was ±0.25 m at 95% confidence level in clear flat areas. Mapping is done manually in GIS by capturing the extents of seagrass beds and patches at a scale of 1:500 and then classifying each area (polygon) into average cover values following the Coastal and Marine Ecological Classification Standard (CMECS) to help align broadscale seagrass data collected nationally (Shanahan *et al.*, 2023) (Table 3). Cover classes define the average amount of seagrass cover (plant presence) versus bare area (absence of plants) visible inside each polygon as they can include bare patches. Some polygons will be areas of small patches aggregated at high density, hence the entire area of aggregated patches is mapped and classified according to the average percentage presence within the polygon. No distinction is made for seagrass cover at the fine scale resolution (generally at scales less than pixel resolution) of whether seagrass blade cover is light with potentially bare sand visible between blades or dense with no substrate visible, as it is extent of seagrass plant occurrence being mapped.

Table 3 Cover values for seagrass based on the Coastal and Marine Ecological Classification Standard.

Coarse percent cover values	Cover class entry GIS
Trace or absent (<1%)	NA
Sparse (1 to <30%)	15
Moderate (30 to <70%)	50
Dense (70 to <90%)	80
Complete (90 to 100%)	95

To ensure consistent mapping accuracy, a protocol was used to guide the mapping process (Appendix 1). Mapping was a desktop exercise, utilising ground-truthing, including historical personal observations in the field and oblique imagery from PhotoOblique to the existence of seagrass beds.

Assessment of total seagrass coverage in any harbour or other defined area is based on summing up the total area mapped in each class, then using the midpoint (i.e., 70%-90% class midpoint = 80%) to calculate out an estimate (average) of the actual area covered for each class and then adding up all the classes of coverage mapped. For Ōhiwa Harbour and the smaller estuaries, all assessments of change are based on a whole harbour/estuary basis. Tauranga Harbour has been divided up into a series of smaller areas to allow for analysis of sub-estuary areas or more open regions of the harbour.

Data presented for earlier surveys (1945, 1959, 1992 and 1996) is based on lower resolution photography (generally 0.5 m - 1 m pixels) and is mapped at a slightly higher scale (1:1,000). From 2000 onwards mapping resolution is slightly higher to take advantage of the improved photography and provide more accurate spatial mapping which gives a clearer picture of how smaller beds or patches are changing over time. Results for average cover are not significantly changed with the higher mapping resolution with the main difference being that the mapped polygons tend to have a higher proportion falling into the dense or complete (80%/95%) classes. There could be a small bias in seagrass extents derived from the pre-2000, lower pixel resolution photography. Generally, the changes in seagrass distribution and overall extent from pre 2000 are far greater than any expected bias from the change in pixel resolution.

2.2 Drivers of seagrass change/Data analysis

To begin to develop an understanding of the processes underlying changes in sea grass cover, we explored relationships between the potential factors influencing seagrass cover within Tauranga Harbour. This included an analysis of catchment water quality trends, estuary water quality trends, and the relationships between environmental factors at a sub-estuary level.

2.2.1 Tauranga Harbour catchment inflow water quality trends

Water quality monitoring data from the Bay of Plenty Regional Council's NERMN programme was used to look for trends in nitrogen and Total Suspended Solids (TSS) loads to Tauranga Harbour as these are two key stressors of seagrass health. Data has been collected from most of the significant streams and rivers flowing to harbour since 1990 with sample collection generally between six and twelve times per year. It has not occurred with equal frequency in all years; hence data sets vary in completeness. Data was checked to remove obvious errors and normality checks made, which required a Log10 transformation to TSS with analysis results converted back to give geometric values.

Flow values at the time of sampling were also incorporated into the data sets to allow the influence of variations in flow to be assessed. Not all streams have flow gauging undertaken at time of samplings, so where there are adjacent catchments, and one has been gauged but not the other, then the proportional relationship between stream flows has been used to estimate flow. Because sampling is never at consistent time frames relative to the peak of higher flow events when these do occur, there is high variability in TSS and nitrogen levels. The flow adjusted TSS, and nitrogen had outliers identified and removed from analysis. Trend analysis was limited to exploration of data using linear regressions.

2.2.2 NIWA-SCENZ water quality products

NIWA-SCENZ[1] (Seas, Coasts and Estuaries New Zealand) is an online tool that provides access to satellite (MODIS-Aqua) water quality images (products), calibrated to New Zealand waters at “moderate” spatial resolutions (~500 m) (Pinkerton *et al*. 2022).

Satellite imagery for nearshore (and estuary areas) is a new addition to the NIWA-SCENZ products and is based on extrapolation: First pixels erroneously located over the land are removed. Next, the data are “de-speckled”, that is, individual pixels very different from those surrounding them are removed. Two methods are then used to estimate missing values within 5 km of the coast: (1) Iterative nearest-neighbour smoothing with a 2.5 km smoothing window; (2) Localised regression extrapolation to estimate missing values from the fitted variation in the property with distance offshore in 10 km-wide transects. Smoothed and extrapolated estimates are then blended using similarity weighting to the surrounding data. Parameters were optimised to maximise the proportion of missing data filled-in and the robustness of the values. Therefore, these products in this report are being used as an estimate of changing patterns over time.

Total suspended sediment concentration (TSS, g/m^3) is an estimate of the total gravimetric concentration of particulate material in the upper water column. It includes both algal (phytoplankton) and non-algal particulates, the latter including inorganic matter (suspended sediment) and non-algal detrital particulate material. The TSS product is derived from a non-linear scaling of particulate backscatter at 555 nm.

Areas of interest were extracted from the northern Tauranga Harbour near Kauri Point, to compare water quality trends and concentrations with the estuary water quality monitoring site at that location. Estuary water quality data is available as monthly samples from 2015.

Additionally, two sites outside the entrances to the northern and southern harbour were extracted to visualise long term coastal trends. Data collated is from 2002 – 2023.

2.2.3 Subestuary analysis

Potential factors influencing the cover of seagrass in Tauranga sub-estuaries was collated to explore relationships (where data was available at a sub-estuary scale) (Table 4).

Linear regression models were used to investigate significant trends and identify correlations amongst variables, including the use of stepwise regression to find the most parsimonious model for current seagrass cover. Histograms were used to check for normality of predictive variables, and optimal transformations were performed to limit the effects of outliers and improve normality. Strong correlations were identified between the water column nutrient concentrations; therefore, a principal component analysis was used with the nutrient data to derive a single nutrient variable for the linear regression, including TN, NO_3, NH_4 and PO_4. Principal component analysis was utilised to visualise patterns amongst the multivariate data and was standardised and transformed prior to analysis.

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1 https://gis.niwa.co.nz/portal/apps/experiencebuilder/template/?id=9794f29cd417493894df99d422c30ec2&page=NIWA-SCENZ

Data from the Tauranga Harbour estuarine ecology network collected between 2015 and 2024 was utilised to assess percentage cover of seagrass against the sediment percentage mud content (69 sites). Percentage cover of seagrass was analysed at each site based on 10 m^2 x 0.25 m^2 quadrats. Sediment percentage mud content was analysed at each site based on 10 cm x 2 cm deep cores pooled into one sample for each site and analysed by laser diffraction at the University of Waikato. The percentage mud content was assessed as the percentage of the sediment sample sized below 63 microns.

Table 4 Detail of the variables used to investigate potential factors influencing the cover of seagrass in Tauranga sub-estuaries.

Variable	Detail
Seagrass cover (ha)	2022 seagrass cover mapped from this report, manually deliminated from aerial imagery
Proportional seagrass cover to sub-estuary area	2022 proportion of sub-estuary area covered by seagrass
Sub-estuary % mud cover	2022 proportion of sub-estuary area covered by sediment with >25% mud content (<63 micron), mapped in GIS using extrapolation from sediment grain size samples (Crawshaw et al. 2022)
SEDNET contemporary catchment load (t/yr)	Modelled sediment loading from the catchment to the estuary from SEDNET (Park et al. 2022) represented by 2018 land cover (LCDB v5)(Vale et al. 2021)
SEDNET contemporary sub-estuary load (t/yr)	Modelled sediment loading from the catchment, and estimated to be retained in the estuary from SEDNET (Park et al. 2022) represented by 2018 land cover (LCDB v5)(Vale et al. 2021)
Modelled estuary water column nutrient concentrations (NO_3, NO_4, PO_4, TN) (g/m^3)	Water column estuary nutrient concentrations from DELWAQ nutrient modelling, data modelled for seasons between 2015-2020 (Bryan & Stewart, 2022)

3 Results/Ngā Otinga

3.1 Tauranga Harbour

Mapping of seagrass in Tauranga Harbour has previously been reported in Park 1999 and 2011, covering the time steps of 1959, 1996 and 2011. Changes in seagrass extent over time are shown in Table 5 and displayed in Figure 2 (note there are slight variations from historical reporting due to mapping protocol changes).

Tauranga Harbour had large historical losses of seagrass evident from 1959 through to 1996 (Park 1999), with a greater proportional loss (around 55%) in the southern harbour compared to the northern harbour (Table 5, Figure 2). In 2022, there has been an overall recovery of seagrass extent in both the northern and particularly the southern harbours, to levels similar to extents mapped in 1996. Current seagrass extent is now 3740 ha, with 1998 ha in the northern harbour, and 1742 ha in the southern harbour. Visually, these changes are shown on a map of Tauranga Harbour in Figure 3. Figure 3A shows a comparison of the current seagrass coverage and how it differs from the mapping in 1959. This highlights significant seagrass expansion in the outer harbour areas with current extent of the whole harbour being 85% of the 1959 historical extent and covering 18% of the harbour area (Table 5). The northern harbour increases in seagrass cover have returned to the same level as 1959.

Table 5 Extent of seagrass cover (hectares) in Tauranga Harbour from aerial photography mapping with percentage of 1959 total harbour extent compared to 2022 and percentage cover of total harbour area.

Year	Total Tauranga Harbour (ha)	Northern harbour (ha)	Southern harbour (ha)	% of 1959 extent	% of harbour area
1959	4,395	2,002	2,394	-	21
1996	2,937	1,855	1,082	66	14
2011	2,740	1,572	1,168	62	13
2022	3,740	1,998	1,742	85	18

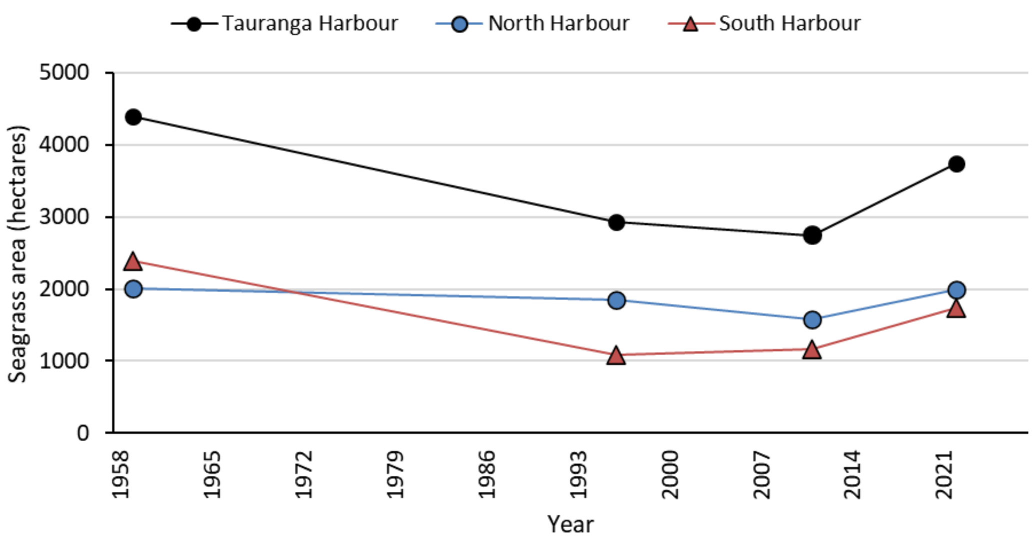

Figure 2 Changes in seagrass extent (hectares) in Tauranga Harbour (black circles and separated into the northern (blue circles) and southern harbour (red triangles).

Seagrass change 1959 to 2022 | Seagrass change 2011 to 2022

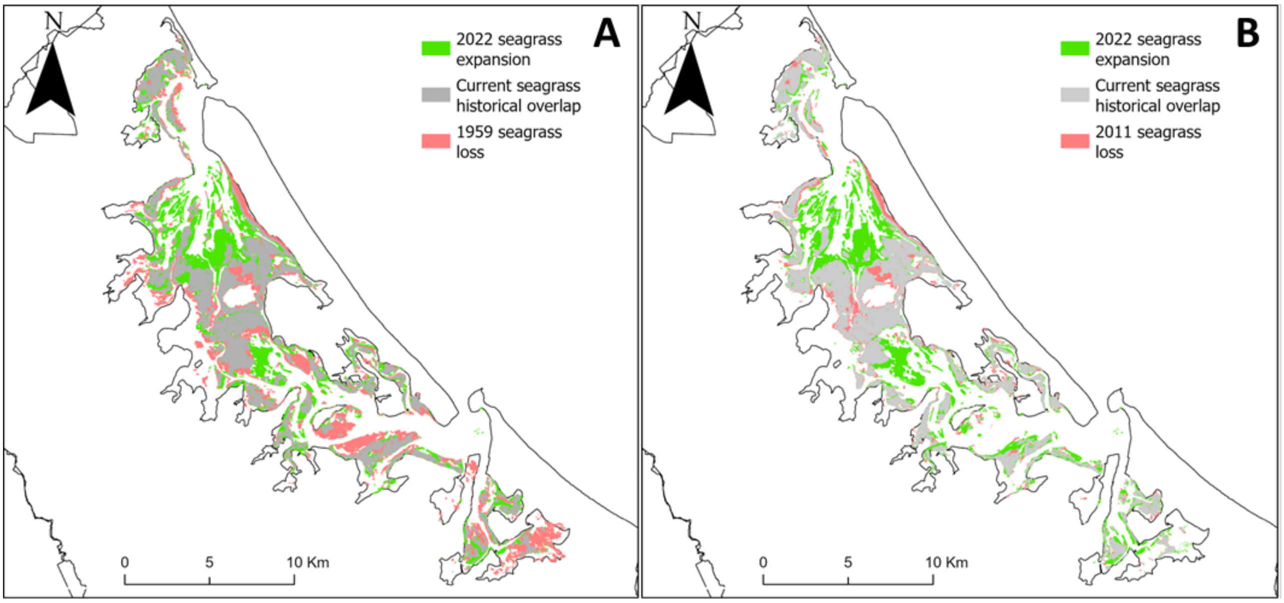

Figure 3 *Change in seagrass extent in Tauranga Harbour mapped by aerial imagery. A: 1959 to 2022 change, B: 2011 to 2022 change. Green = most recent expansion, Grey = current seagrass coverage that overlaps the reported historical coverage, Red = areas of seagrass loss between historical and current.*

Previous mapping had shown that between 1959 and 1996 the pattern of greatest seagrass loss around the whole of Tauranga Harbour was in the sub-estuaries with the larger catchments and freshwater inflows (Park 1999). Although the 2022 mapping is showing extensive increase in seagrass abundance since the 2011 mapping, most of that increase is in the open harbour areas (Figure 3B). Tauranga Harbour has a large number of sub-estuaries that are influenced by differing land uses, flushing times and influence from freshwater (Crawshaw *et al*. 2022).

In Table 6 it can be seen that many of the sub-estuaries receiving significant freshwater inflows still have a low proportion of seagrass compared to the 1959 extents. The exceptions are Mangawhai and Te Puna, both of which have higher abundance than 1959 and have been increasing since 1996. The sub-estuary still showing high loss with little if any recent improvement in abundance includes Uretara, Aongatete, Waikareao, Waimapu, Welcome Bay and Rangataua Bay.

Table 6 *Extent of seagrass cover (hectares) in Tauranga Harbour sub-estuaries from 1959 to 2022 mapping with percentage of 1959 extent compared to 2022.*

Sub-estuary	1959 (ha)	1996 (ha)	2011 (ha)	2022 (ha)	% of 1959 extent
Waiau	25.7	24.3	14.3	18.5	72.2
Tuapiro	9.1	16.9	12.2	6.6	72.7
Uretara	13.5	6.0	4.5	7.2	52.9
Blue Gum	215.5	218.5	215.5	141.2	65.6
Rereatukahia	31.1	8.6	8.9	20.3	65.3
Aongatete	60.8	0	0.1	0.1	0.2

Sub-estuary	1959 (ha)	1996 (ha)	2011 (ha)	2022 (ha)	% of 1959 extent
Mangawhai	53.7	24.0	42.5	68.2	127.1
Hunters	322.2	204.3	179.2	205.9	63.9
Waipapa	107.7	45.0	50.4	78.9	73.2
Te Puna	22.3	12.0	20.4	26.0	116.4
Waikaraka	3.1	0.9	1.4	1.3	42.3
Wairoa	269.8	128.3	105.3	147.5	54.7
Waikareao	6.0	0.7	1.3	0.3	4.7
Waimapu	0.7	0.0	0.0	0.01	1.8
Welcome	14.1	2.5	2.0	0.6	4.2
Rangataua	184.7	40.7	25.5	36.7	19.8

3.1.1 Subtidal seagrass

In the subtidal zone, there has been a significant expansion of new seagrass since the 2011 mapping. Subtidal seagrass extent is shown in Figure 4, showing the large new areas of subtidal seagrass in the north estuary and upper estuary. Historically, subtidal seagrass was sparse in the northern harbour, and in 1959 was mostly in the southern harbour (Figure 5, Table 7) (Park 1999). Recent expansion of subtidal seagrass has mainly been in the north, where cover now greatly exceeds that in 1959, occupying areas where seagrass has not been previously mapped. In the southern harbour, subtidal cover has also expanded over 2011, but has yet to recover to the area seen in 1959.

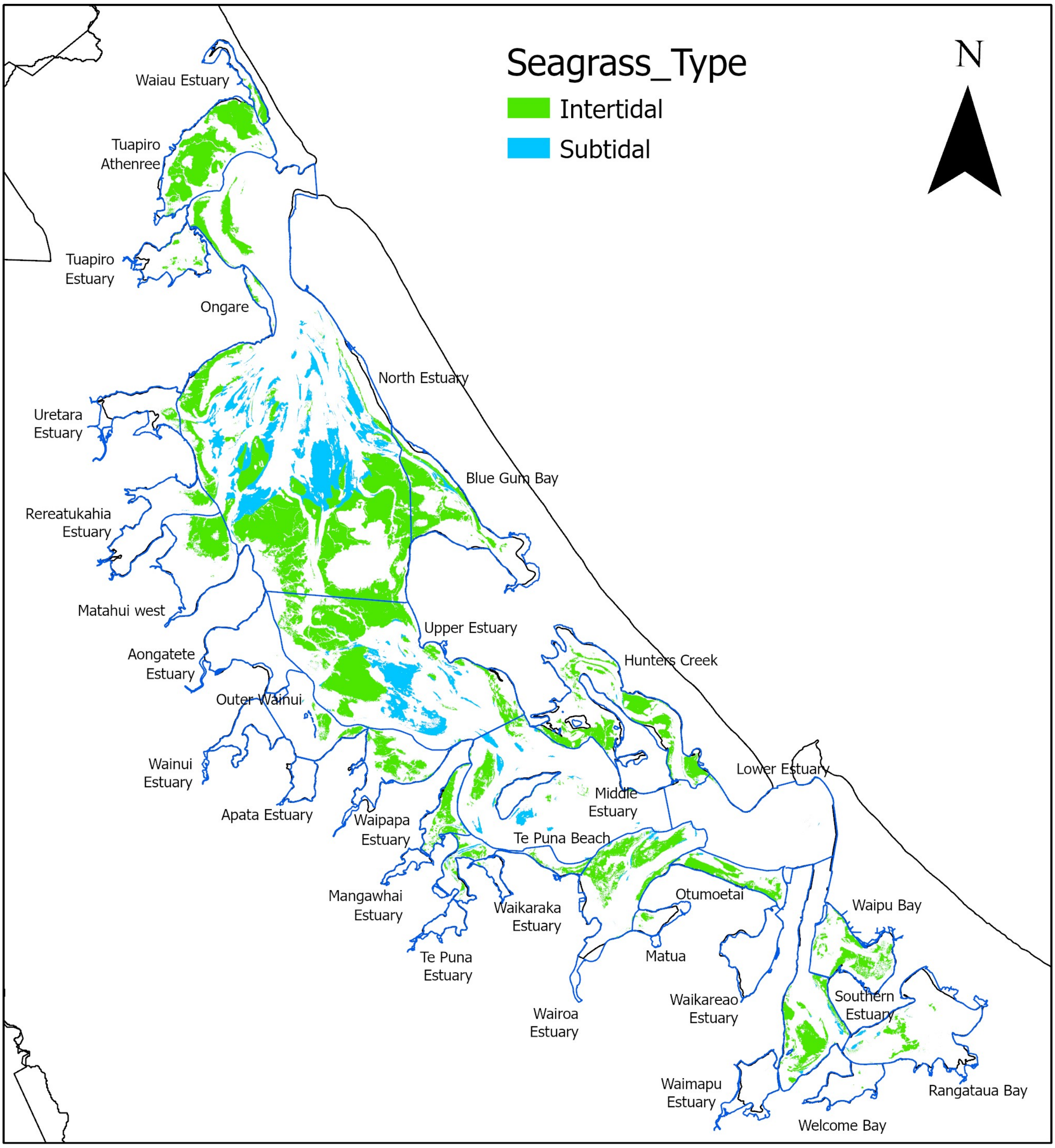

Figure 4 *2022 intertidal (green) and subtidal (blue) seagrass mapped in Tauranga Harbour. Sub-estuary boundaries (dark blue) and names are displayed.*

Table 7 *Tauranga Harbour subtidal seagrass extents (ha) and as a percentage of the total seagrass extents (intertidal and subtidal) for the defined regions over time.*

Year	Total harbour		Northern harbour		Southern harbour	
	Subtidal extent (ha)	% of all seagrass	Subtidal extent (ha)	% of all seagrass	Subtidal extent (ha)	% of all seagrass
1959	479	10.9	74	3.7	405	16.9
1996	46	1.6	24	1.3	22	2.0
2011	30	1.1	12	0.8	18	1.5
2022	659	17.6	449	22.5	210	12.1

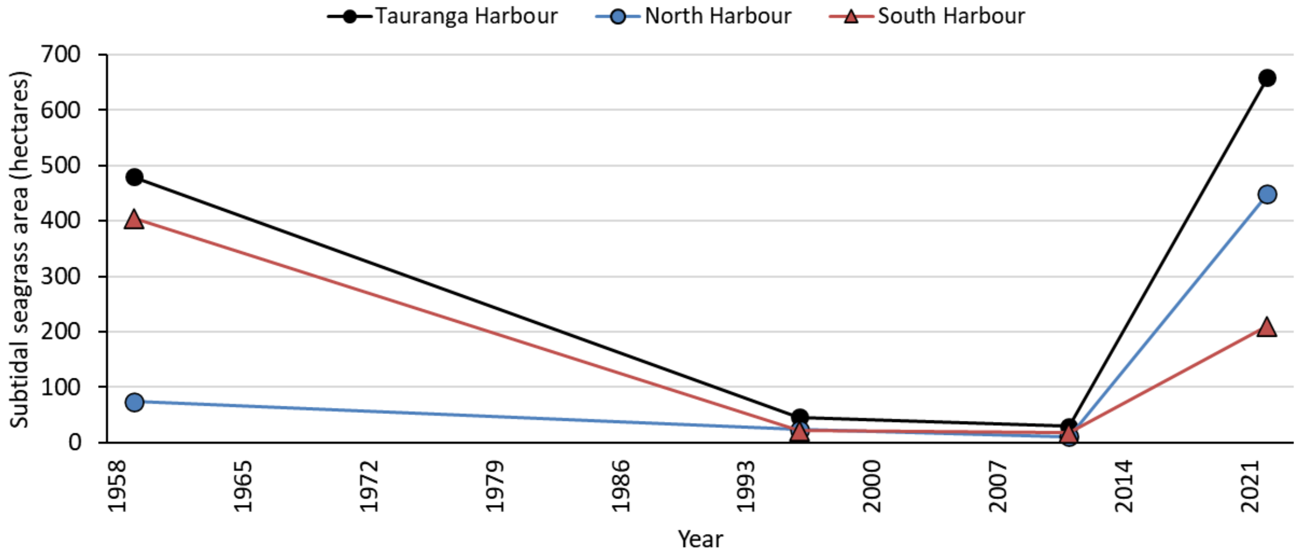

Figure 5 *Changes in subtidal seagrass extent (hectares) in Tauranga Harbour (black circles) and separated into the northern (blue circles) and southern harbour (red triangles).*

3.2 Maketū Estuary

Seagrass in Maketū Estuary has been declining since 1961 (Park 2014, 2016, 2018a, 2022). Since the last reporting on seagrass cover, the Kaituna River re-diversion project has been completed in 2020, which has restored 20% of the Kaituna River's freshwater flows back into Maketū Estuary and created new saltmarsh habitat within the Te Pā Ika wetland. There has been a rapid recovery of a number of estuary parameters, including declining macroalgae cover and mud content at sites in the upper estuary.

Historically there has been a decline of seagrass in the estuary, dropping below 1 ha between 1977 and 1994 (Table 8, Figure 6). These small patches remained until 2019, where the seagrass disappeared from the estuary. The seagrass in Maketū has begun to re-establish since 2020, with numerous small patches returning to a site in the lower estuary (Figure 7). In 2022, the total seagrass cover was 0.006 ha (or 60 m^2), only 0.12% of the extent in 1939. Figure 8 shows the historical distribution spatially, and highlights the large areas lost since 1939 (Figure 8A). Figure 8B shows the recovery of small patches between 2020 and 2022, located at the eastern end of the estuary close to the mouth. Further recovery of the seagrass in Maketū is currently being limited by high grazing activity by black swans in the estuary on the recovering seagrass patches. The high extent of muddy sediment throughout the upper estuary also limits where seagrass could occur.

Table 8 *Extents of seagrass cover (hectares) in Maketū Estuary from aerial photography mapping. Percentage of seagrass remaining of historical extent (earliest reported cover) and percentage cover of the estuary area.*

Year	Total (ha)	% remaining of historical extent	% cover of estuary area
1939	4.78	100	2.03
1948	13.19	276	5.59
1961	2.17	45	0.92
1977	4.35	91	1.84

Year	Total (ha)	% remaining of historical extent	% cover of estuary area
1994	0.0008	0.02	0.0003
2003 - 2016	0.0004	0.01	0.0002
2017/2018	0.0002	0.004	0.0001
2019	0	0	0
2020	0.00002	0.0004	0.00001
2021	0.015	0.30	0.006
2022	0.006	0.12	0.002

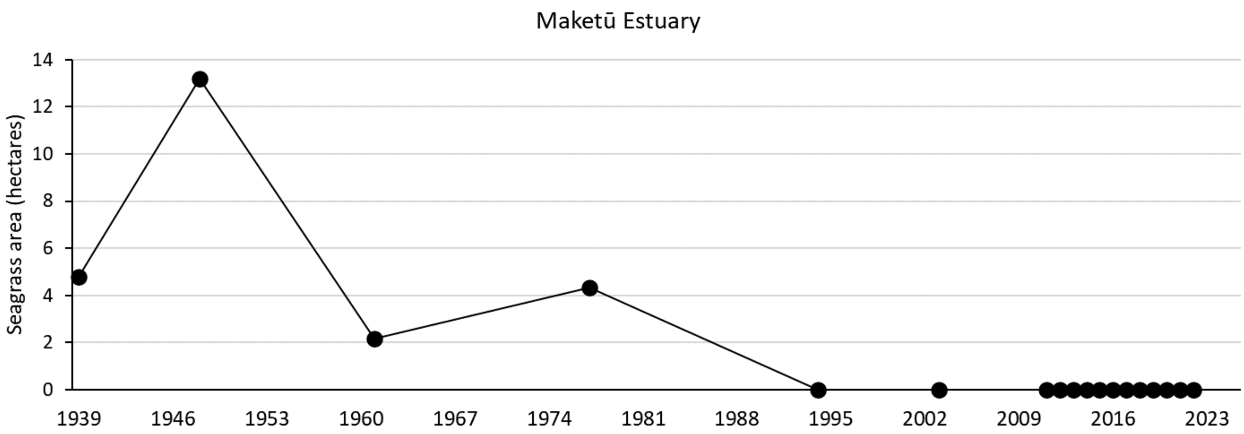

Figure 6 Changes in seagrass extent (hectares) over time in Maketū Estuary (black circles).

Figure 7 Small patches of seagrass in Maketū Estuary in 2023. Left = closeup patch of seagrass. Right = aerial photo of seagrass patches, highlighted by black box (Photo credit: PhotoOblique).

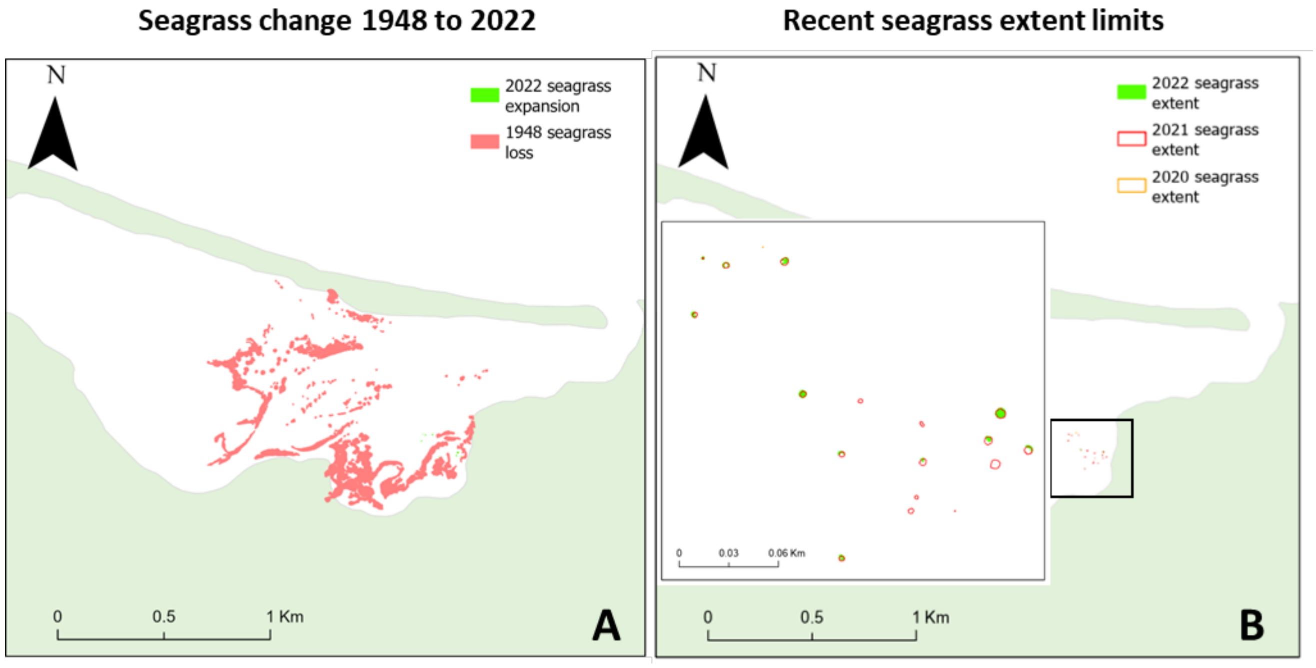

Figure 8 *Change in seagrass extent in Maketū Estuary mapped by aerial imagery. A: 1948 to 2022 change, B: Latest three years of aerial mapping (includes inset zoom in black box). Green = most recent expansion, Grey = current seagrass coverage that overlaps the reported historical coverage, Red = areas of seagrass loss between historical and current.*

3.3 Waihī Estuary

Waihī Estuary has shown declining trends in seagrass cover since 1943 (Table 9, Figure 9), driven by channelisation of rivers, drainage of wetlands and an increase in nutrient and sediment inputs (Park 2016, 2018a). In 2022, seagrass extent in Waihī Estuary is 0.86 ha, 1% of the historical extent in 1943, and covering only 0.26% of the estuary area. Figure 10A shows the significant spatial expanse of seagrass that existed in 1943, and Figure 10B shows the small remaining patches along the Pukehina spit that have been stable for several years. Modelling of seagrass growth in Waihī Estuary (Chakravarthy et al. 2021) closely matched spatial extents and identifies sediment and nutrients as key drivers of the environmental stressors limiting growth.

Table 9 *Extents of seagrass cover (hectares) in Waihī Estuary from aerial photography mapping. Percentage of seagrass remaining of historical extent (earliest reported cover) and percentage cover of the estuary area.*

Year	Total (ha)	% remaining of historical extent	% cover of estuary area
1943	78.49	100	23.50
1963	16.83	21.4	5.04
1981	16.75	21.3	5.01
2007	2.52	3.2	0.75
2011	1.82	2.3	0.55
2015	1.58	2.0	0.47
2018	1.22	1.6	0.36
2019	0.99	1.3	0.30
2020	0.79	1.0	0.24
2022	0.86	1.1	0.26

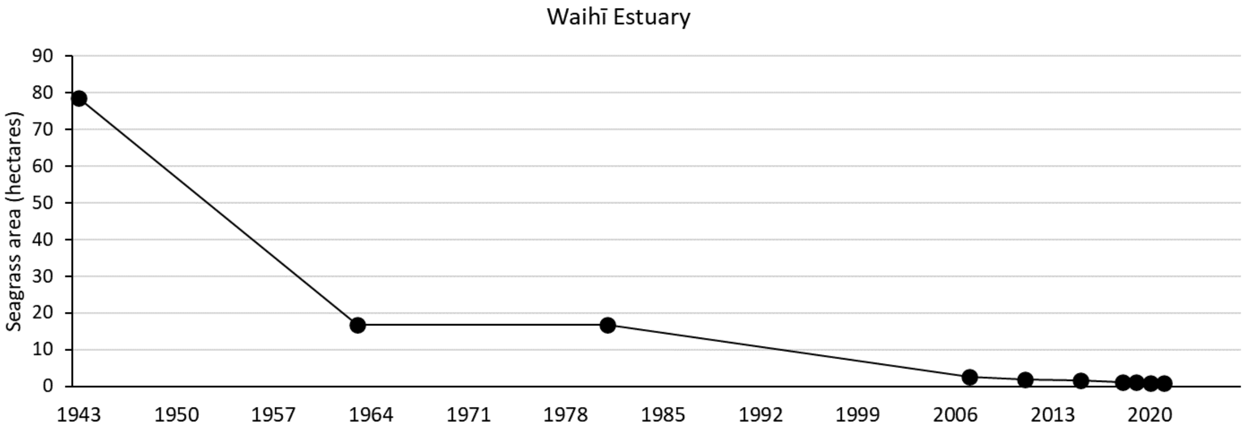

Figure 9 *Changes in seagrass extent (hectares) over time in Waihī Estuary (black circles).*

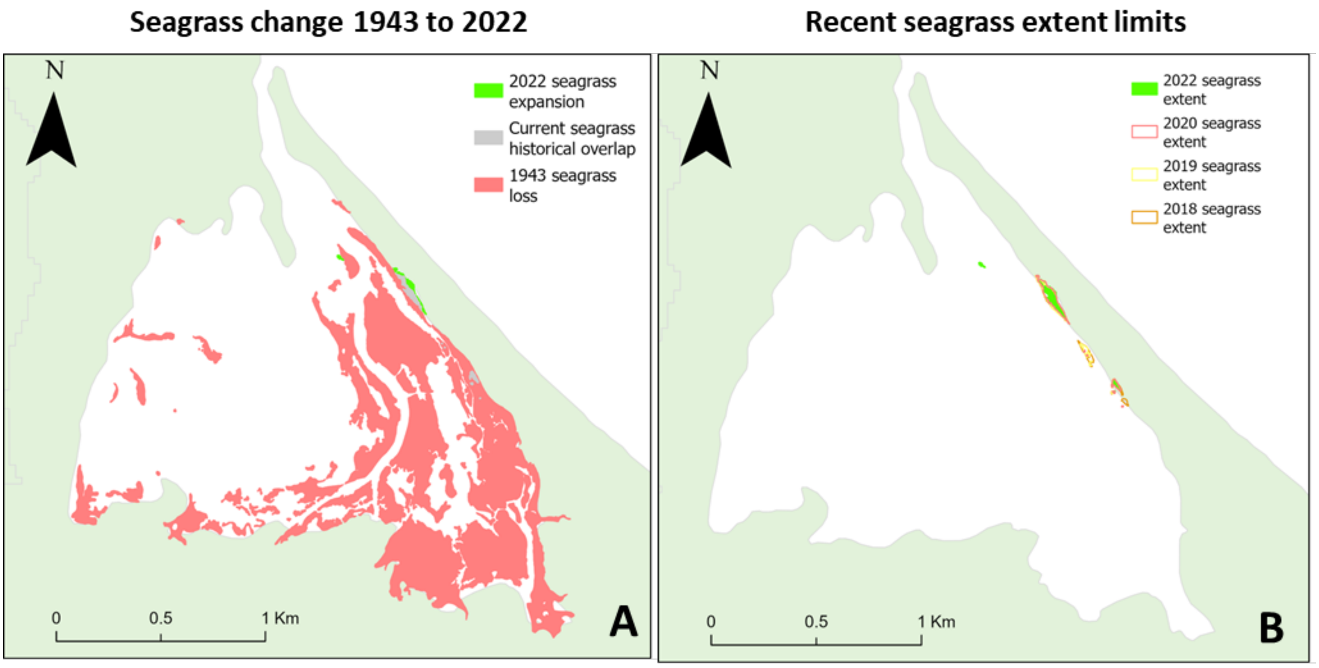

Figure 10 *Change in seagrass extent in Waihī Estuary mapped by aerial imagery. A: 1943 to 2022 change, B: Latest four years of aerial mapping. Green = most recent expansion, Grey = current seagrass coverage that overlaps the reported historical coverage, Red = areas of seagrass loss between historical and current.*

3.4 Ōhiwa Harbour

Ōhiwa Harbour has had previous records of declining seagrass cover (Park 2016), followed by a short period of recovery in 2007-2011, then further declines reported through to 2022 (Table 10, Figure 11). The current seagrass coverage is 63.7 ha, representing 53% seagrass extent remaining from the 1945 mapping, and only covering 2.8% of the harbour area (Table 10). Figure 12 visualises spatially where the changes in seagrass coverage has occurred. Comparing the current seagrass extent to the 1945 coverage (Figure 12A), it is evident that losses of seagrass occurred in the sheltered upper harbour areas closer to the inflows from land. Some minor expansion has occurred compared to 1945, with seagrass extending towards the mouth of the harbour. When comparing changes from 2014 to 2022 (Figure 12B), losses of seagrass have occurred primarily to the west of the harbour, including a loss of seagrass along the Ōhiwa spit. No subtidal seagrass has been identified in Ōhiwa Harbour which includes extensive dive surveys over many years.

Table 10 Extents of seagrass cover (hectares) in Ōhiwa Harbour from aerial photography mapping. Percentage of seagrass remaining of historical extent (earliest reported cover) and percentage cover of the estuary area.

Year	Total seagrass area(ha)	% remaining of historical extent	% cover of estuary area
1945	121.0	100	5.3
1992	88.0	73	3.9
1996	83.3	69	3.7
2007	101.8	84	4.5
2011	100.5	83	4.4
2014	89.7	74	3.9
2022	63.7	53	2.8

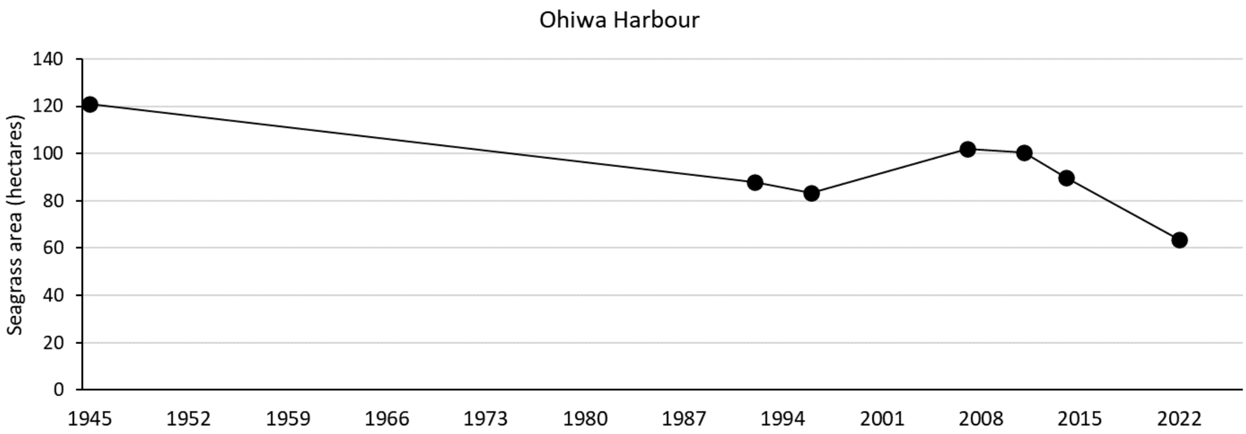

Figure 11 Changes in seagrass extent (hectares) over time in Ōhiwa Harbour (black circles).

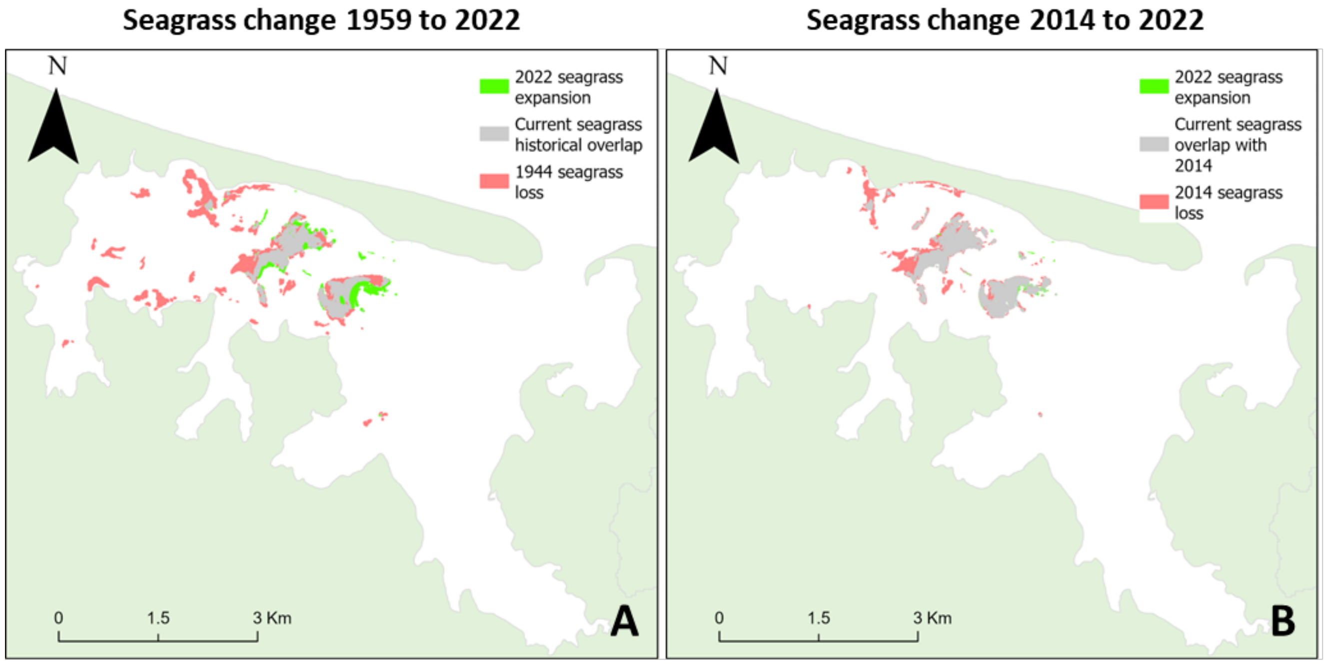

Figure 12 Change in seagrass extent in Ōhiwa mapped by aerial imagery. A: 1959 to 2022 change, B: 2014 to 2022 change. Green = most recent expansion, Grey = current seagrass coverage that overlaps the reported historical coverage, Red = areas of seagrass loss between historical and current.

3.5 Waioeka Estuary (Ōpōtiki, Huntress Creek)

The Waioeka Estuary (or Ōpōtiki Estuary) has historically had a small region of intertidal sandflats that supports seagrass cover, on the western edges of the Waioeka River in Huntress Creek. Seagrass has declined over time in the estuary (Table 11, Figure 13), due to large modifications of the land surrounding the western edges of the estuary, including reclamation for farming. This seagrass cover was predominantly subtidal within the channels of saltmarsh habitats. The seagrass extent in 2022 is restricted to intertidal areas in Huntress Creek, to the west of the estuary/river covering 0.19 ha. The current seagrass extent represents 5% of the historical seagrass extent, covering 0.1% of the estuary area. Figure 14A shows the 1940 spatial distribution of seagrass relative to the distribution today, and Figure 14B highlights the areas of seagrass loss from 2014 to 2022, where the seagrass has disappeared from the subtidal channel edges.

The Waioeka Estuary is currently undergoing significant modifications to the river mouth, creating a new harbour entrance to allow for larger shipping movements into the estuary. The modelling scenarios indicate that little change in the salinity and other water quality parameters are expected with the changes to the entrance. Hence, the current decline in seagrass extent may continue.

Table 11 *Extents of seagrass cover (hectares) in Waioeka Estuary from aerial photography mapping. percentage of seagrass remaining of historical extent (earliest reported cover) and percentage cover of the estuary area.*

Year	Total (ha)	% remaining of historical extent	% cover of estuary area
1940	4.09	100	3.1
2003	2.08	51	1.6
2007	2.83	69	2.2
2011	3.14	77	2.4
2014	1.69	41	1.3
2022	0.19	5	0.1

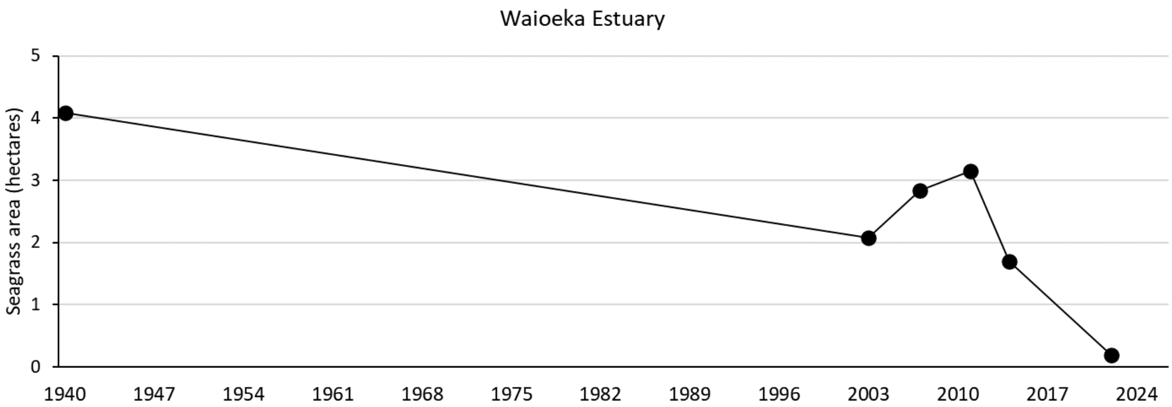

Figure 13 *Changes in seagrass extent (hectares) over time in Waioeka Estuary (black circles).*

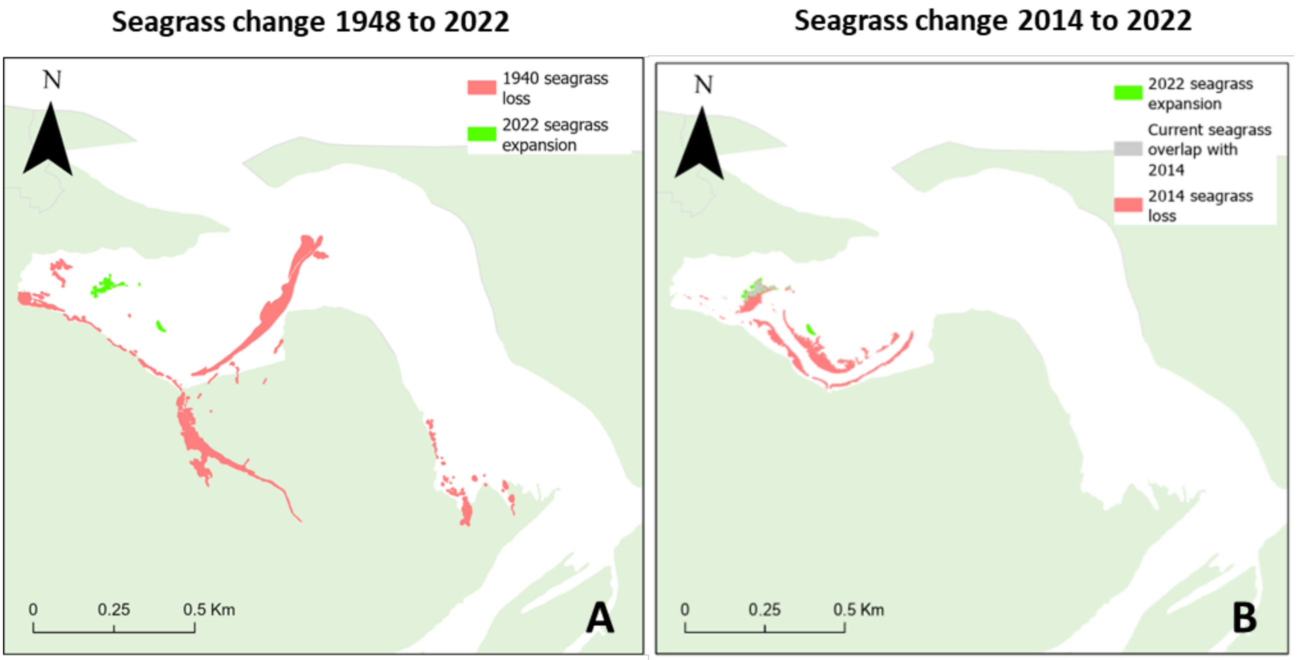

Figure 14 *Change in seagrass extent in Waioeka Estuary mapped by aerial imagery. A: 1940 to 2022 change, B: 2014 to 2022 change. Green = most recent expansion, Grey = current seagrass coverage that overlaps the reported historical coverage, Red = areas of seagrass loss between historical and current.*

3.6 Entire Bay of Plenty

Across the entirety of the estuaries in the Bay of Plenty, it is evident there have been significant declines in seagrass cover. When compared to estuary size, Waihī Estuary historically held the highest seagrass percentage cover of all the estuaries, prior to catchment and wetland degradation (Figure 15). Relative to size, Tauranga Harbour hosts the greatest coverage of seagrass and appears to have some resilience and capacity for recovery, compared to the smaller estuaries of Waihī and Maketū where seagrass is functionally lost from the system. Ōhiwa Harbour has shown some historical resilience and recovery of seagrass.

The historical mapping baseline of seagrass cover gives us the best estimate of seagrass cover prior to large scale catchment modification (although some had occurred prior, including drainage of large areas of wetlands). Tauranga and Ōhiwa Harbours both currently retain between 50% – 80% of the historical seagrass cover, which indicates a level of resilience, and/or less catchment pressures than the smaller estuaries (Figure 16). Both Maketū and Waihī Estuaries hold only a minute fraction (<1%) of the historical cover.

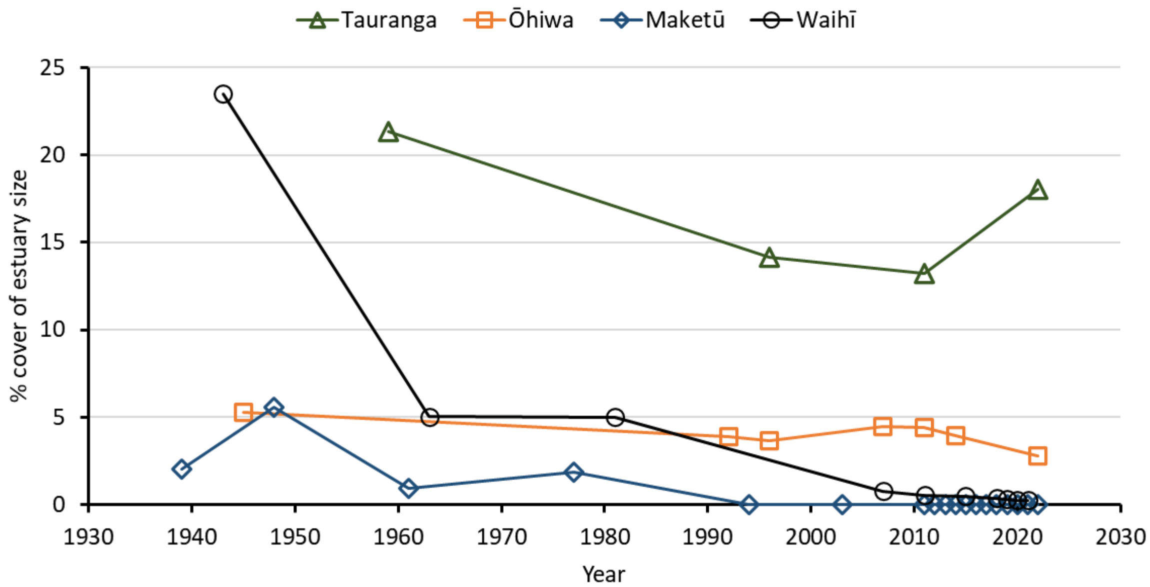

Figure 15 *Seagrass extent as a percentage of estuary size over time mapped from aerial imagery. Green triangles = Tauranga Harbour, Grey squares = Ōhiwa Harbour, Blue diamond's = Maketū Estuary, Black circles = Waihī Estuary.*

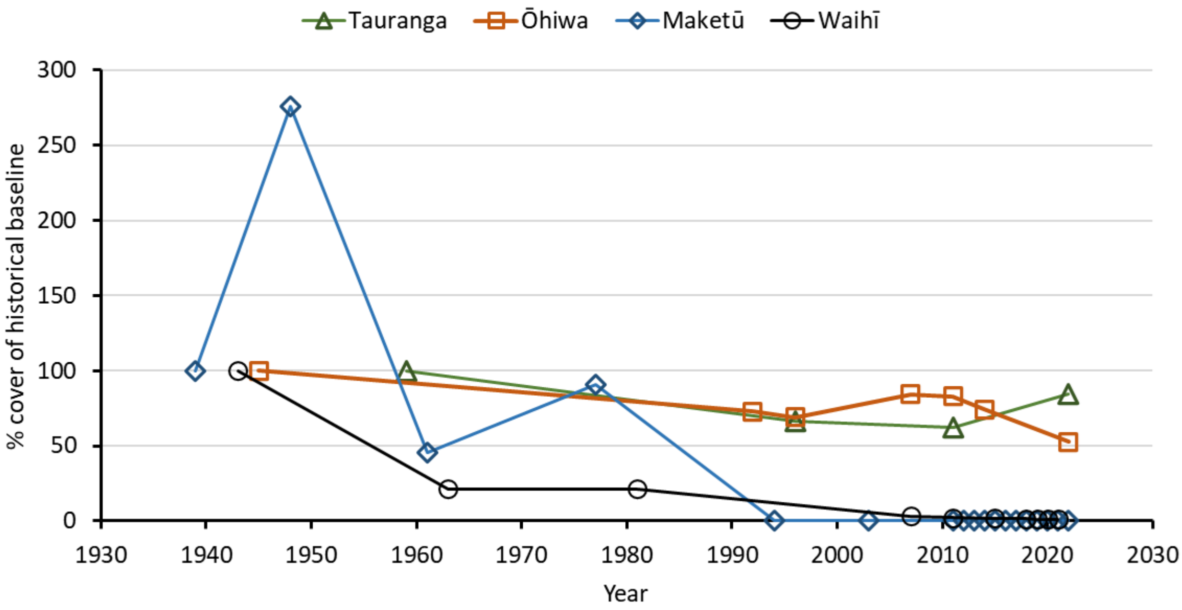

Figure 16 *Seagrass extent as a percentage of the historical baseline (earliest mapping period) over time mapped from aerial imagery. Green triangles = Tauranga Harbour, Grey squares = Ōhiwa Harbour, Blue diamond's = Maketū Estuary, Black circles = Waihī Estuary.*

3.7 Drivers of seagrass change

The extensive recovery in parts of the Tauranga Harbour suggests that growth conditions, particularly for submerged seagrass, appears to have improved. Therefore, this section examines available information to determine what may have changed to allow this recovery to have occurred.

3.7.1 Tauranga Harbour catchment water quality trends

Thirteen Tauranga Harbour rivers and streams were assessed for trends in nitrogen and TSS over the 1990 to 2023 time period. The median values for each stream are provided in Table 12 below along with the number of samples (in brackets). The Waiau, Tuapiro, Uretara, Rereatukahia, Te Mania and Waitekohe Streams flow into the northern Tauranga Harbour basin and tend to have smaller catchments and as shown in Table 12 below, median concentrations of nitrate/nitrite (NO_x), Total Nitrogen and Total Suspended Solids tend to be lower than the southern harbour inflows.

Table 12 Median concentrations for NOx, Total Nitrogen and Total Suspended Solids (as a geometric value) and the number of samples (in brackets) for Tauranga Harbour stream inflows sampled from 1990 to 2023.

Stream/river	NO_x – g/m^3	TN – g/m^3	TSS (geometric) g/m^3
Northern harbour			
Waiau	0.249 (155)	0.335 (150)	2.162 (155)
Tuapiro	0.078 (157)	0.156 (154)	0.995 (161)
Uretara	0.187 (198)	0.261 (197)	1.133 (184)
Rereatukahia	0.320 (220)	0.398 (218)	0.995 (219)
Te Mania	0.258 (308)	0.420 (306)	5.310 (310)
Waitekohe	0.083 (238)	0.170 (239)	0.995 (242)
Southern harbour			
Aongatete	0.243 (163)	0.331 (163)	0.995 (162)
Waipapa	0.516 (195)	0.615 (194)	1.399 (195)
Omanawa	1.090 (319)	1.210 (306)	11.589 (326)
Kopurererua	0.921 (285)	1.061 (286)	15.998 (320)
Waimapu	0.758 (251)	0.931 (250)	6.998 (256)
Waitao	0.447 (234)	0.608 (234)	5.998 (237)
Rocky	0.734 (200)	1.230 (199)	4.600 (201)

3.7.2 Nitrate/nitrite Long-term trends

Linear regression results for nitrate, nitrogen and TSS are displayed in Table 13. Linear regression results for nitrate/nitrite show “very likely” long-term trends (95%-99% confidence level) showing increasing levels in the Te Mania Stream and Waimapu River. “Virtually certain” trends (>99% confidence) were detected for the Omanawa River and Kopurererua Stream showing increases while the Waitao and Rocky Streams show declining concentrations. However, after exploring the relation with flow and adjusting for any association, there were no significant increasing trends detected (Table 13 below) apart from the Omanawa and Kopurererua which also had no significant association with stream flow levels, hence do not have results for flow adjustment. Flow adjustment results in an overall trend of greater decline in NO_x concentrations from all sites as a result of removing variation associated with the underlying changes driven by wetter and drier periods of climate. In the early 1990’s when most sampling was first undertaken the climate was very dry and the end of the data period (2023) was very wet which strongly influences the overall linear trend.

3.7.3 Total Nitrogen long-term trends

Linear regression results for Total nitrogen show “very likely” long-term declining trends for Waitekohe Stream and “virtually certain” for Waipapa, Waitao and Rocky Streams in TN. However, once adjustment is made for stream flow, then most streams show a reduction in TN concentrations (Table 13). Omanawa River and Kopurererua Stream are the only two not to show a decline in TN concentrations. As with the NOx results, attempting to adjust for wetter and drier periods of climate has increased the detectable level of TN decline over the 1990 – 2023 period.

3.7.4 Total Suspended Solids long-term trends

Linear regression results for Total Suspended Solids show Uretara Stream has a “very likely” long-term declining trend, while Te Mania and Kopurererua Stream have “virtually certain” declining trends based on non-flow adjusted data. Adjusting for stream flow results in the Waiau, Tuapiro, Omanawa and Waitao Streams showing a “very likely” decline and Uretara, Rereatukahia, Te Mania, Waipapa, Kopurererua and Waimapu all showing “virtually certain” declines in TSS concentrations.

A full set of tables for NO_x, TN and TSS are provided in the Appendix 3.

Table 13 The amount of change in absolute value (g/m^3) and the percentage change per year from the linear regression of NOx, TN and TSS data from 1990 to 2023 for Tauranga Harbour stream inflows. All results are flow adjusted data except those marked by an asterisk. Level of significance is displayed in colour, red = virtually certain: >99% confidence, yellow = very likely: 95% - 99% confidence.

Stream/river	NO_x		TN		TSS	
	Change/y	%change/y	Change/y	%change/y	Change/y	%change/y
Northern harbour						
Waiau	-0.00033	-0.13	**-0.00219**	**-0.65**	-0.00837	-0.39
Tuapiro	-0.00073	-0.94	**-0.00073**	**-0.47**	-0.00837	-0.84
Uretara	-0.0011	-0.59	**-0.0073**	**-2.80**	**-0.03306**	**-2.92**
Rereatukahia	-0.00219	-0.68	**-0.0073**	**-1.83**	**-0.03306**	**-3.32**
Te Mania	0.00073	0.28	**-0.00365**	**-0.87**	**-0.03306**	**-0.62**
Waitekohe	-0.00073	-0.88	**-0.0073**	**-4.29**	-0.00837	-0.84
Southern harbour						
Aongatete	-0.00183	-0.75	**-0.00365**	**-1.10**	-0.0067	-0.67
Waipapa	**-0.0073**	**-1.41**	**-0.0073**	**-1.19**	**-0.01667**	**-1.19**
Omanawa	**0.01450***	**1.34***	0.0110*	0.90*	**-0.00837**	**-0.07**
Kopurererua	**0.00730***	**0.79***	0.00365*	0.31*	**-0.01667**	**-0.10**
Waimapu	-0.00256	-0.34	**-0.0073**	**-0.78**	**-0.01667**	**-0.24**
Waitao	**-0.01095**	**-2.45**	**-0.0073**	**-1.20**	**-0.00837**	**-0.14**
Rocky	**-0.01825**	**-2.49**	**-0.03285**	**-2.67**	0.005055	0.11

3.7.5 NIWA-SCENZ estuary water clarity trends

NIWA-SCENZ products are extrapolated from offshore to inshore, to fill in gaps in satellite imagery that is often missing. To compare its validity for use of concentrations within the harbour, we compare “grab” sampling data from the northern Kauri Point site to a broader extract of points from the northern harbour from NIWA-SCENZ. This identifies higher concentrations in the grab samples, as NIWA-SCENZ outputs are “biased” by lower levels in the open coastal zone (Figure 17). The estuary water quality samples also show higher TSS variability due to rainfall events and combined with the short period of data, no linear trends were detectable. However, the grab samples from Kauri Point do show variation that matches rainfall variation.

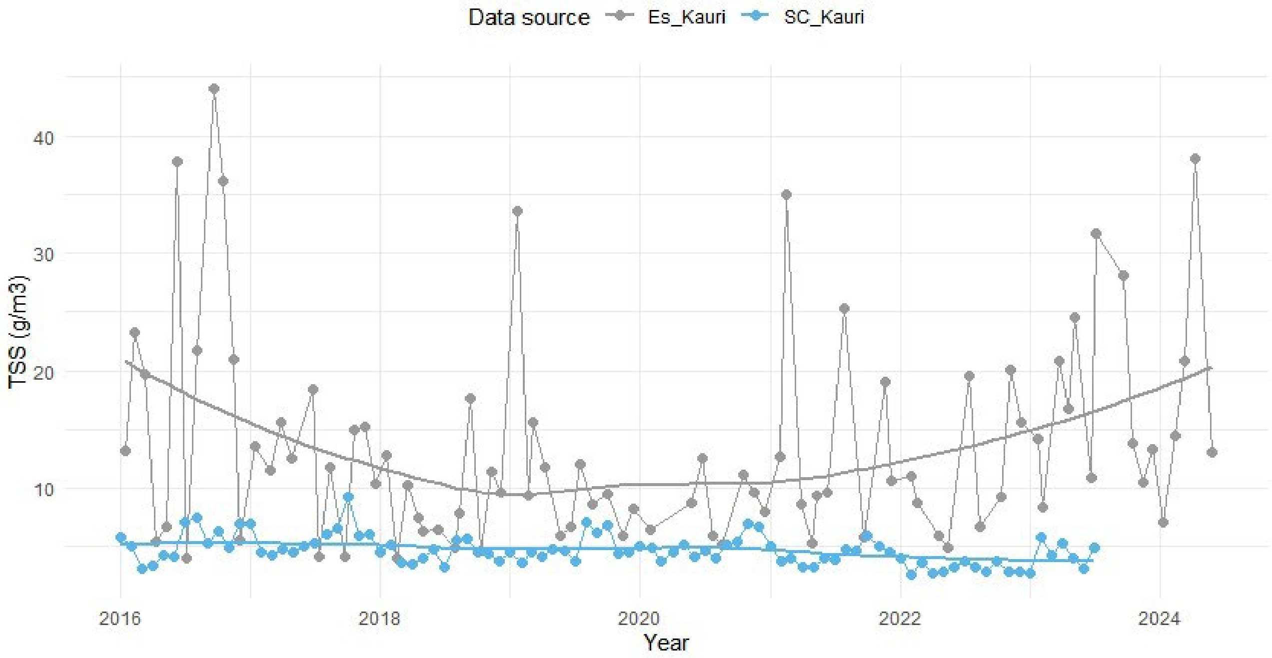

Figure 17 *Total suspended solids (TSS, g/m^3) for the estuary water quality site at Kauri Point (grey) compared to NIWA-SCENZ in blue. Outliers above 50 removed. A loess curve is fitted to the data.*

To investigate longer term patterns in TSS for Tauranga Harbour, we utilised data from NIWA-SCENZ from an area outside the northern and southern entrance (Figure 18). Similar concentrations are reported for both northern and southern ends of the harbour and have been trending up in recent years with increased rainfall/storm activity, particularly notable for the very wet 2023 year.

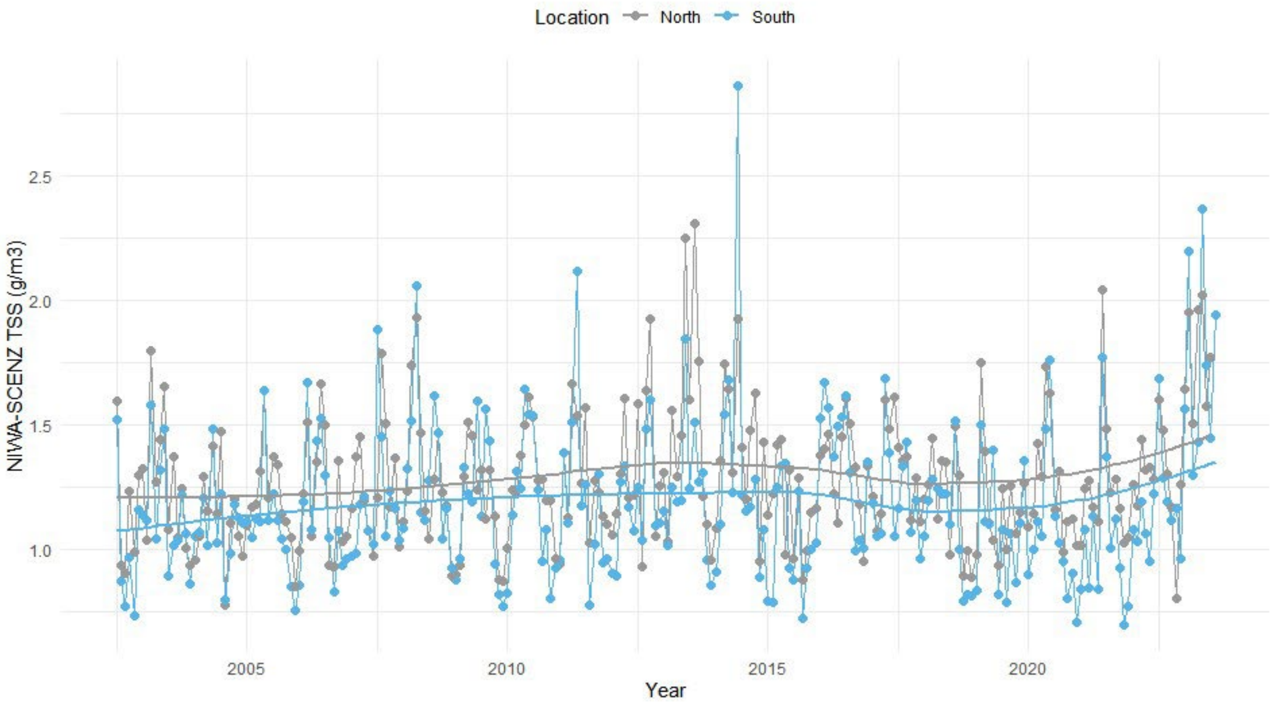

Figure 18 *Total suspended solids (TSS, g/m^3) for the northern (grey) and southern (blue) Tauranga Harbour entrance sites from NIWA-SCENZ. A loess curve is fitted to the data.*

3.7.6 Environmental pressures influencing seagrass cover

The Tauranga Harbour sub-estuaries were utilised to investigate possible factors influencing the cover of seagrass in 2022 (Table 14). This focused on the sub-estuaries that contain a distinct connection to the coast, and often a direct riverine source.

A principal component analysis was used to visualise the relationship between seagrass cover, and the possible predictive variables (Figure 19). The first dimension of the PCA is comprised of the water column nutrients, explaining 43.3% of the variance observed. The second dimension of the PCA is the seagrass cover, related negatively to the sediment variables, including sub-estuary % mud cover and SEDNET retained sediment load, explaining 26.3% of the variance. This identifies the sites more influenced by sediment, including Aongatete, Waimapu, Welcome Bay, Uretara, Wainui, Rereatukahia and Tuapiro. Those sites influenced by higher dissolved water column nutrients include Waikareao, Waimapu, Matua, Matahui and Wairoa. The sites that have a higher seagrass cover, and lower influence from sediment and nutrients include Hunters Creek, Blue Gum Bay, Mangawhai and Waipu Bay. The PCA illustrates that nutrient concentrations within the estuary co-vary, with little evidence to link seagrass cover. However, sub-estuary % mud cover and retained sediment load are related, and inversely correlated to seagrass cover.

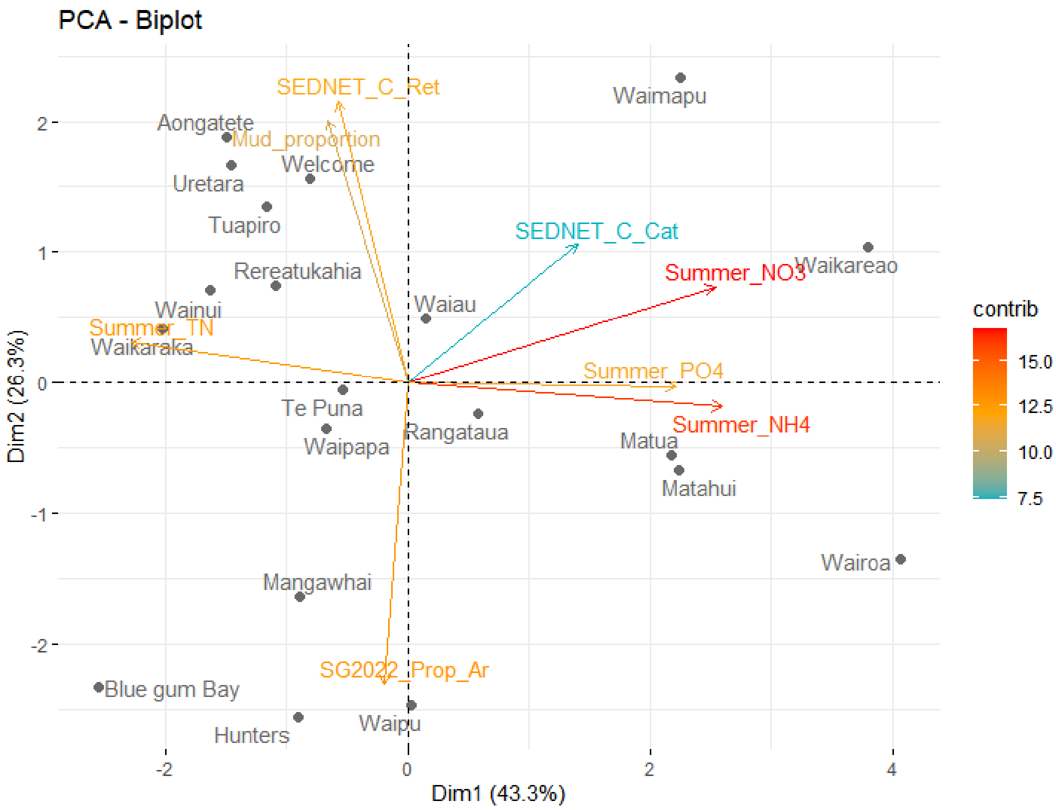

Figure 19 Principal component analysis for seagrass cover in 2022 and environmental drivers. Site names are shown in grey. % contribution of variables to the principal component are coloured by 'contrib'. 'Mud_proportion' is the sub-estuary % mud cover 'SEDNET_C_Ret' is the SEDNET model estimated catchment sediment load retained in the estuary, 'SEDNET_C_Cat' is the SEDNET model estimated catchment sediment load delivered to the estuary, 'SG2022_Prop_Ar' is the proportion of the estuary area covered by seagrass, and 'Summer_TN, PO4, NH4, NO3' is the estimated summer estuary water nutrient concentrations from modelling (Bryan & Stewart, 2022).

Stepwise linear regression identified the sub-estuary % mud cover as the strongest predictor of proportional seagrass cover ($R^2 = 0.30$, $F(1, 18) = 7.55$, $p = 0.013$). There was also a negative relationship between proportional seagrass cover and catchment sediment load retained ($R^2 = 0.22$, $F(1, 18) = 5.0$, $p = 0.038$). Figure 20 visualises these relationships, identifying that sub-estuary proportional seagrass cover appears unlikely to exceed ~5% when the sub-estuary % mud cover is greater than ~30%, or when the catchment sediment load retained is above 1 – 5 g/m^2/day.

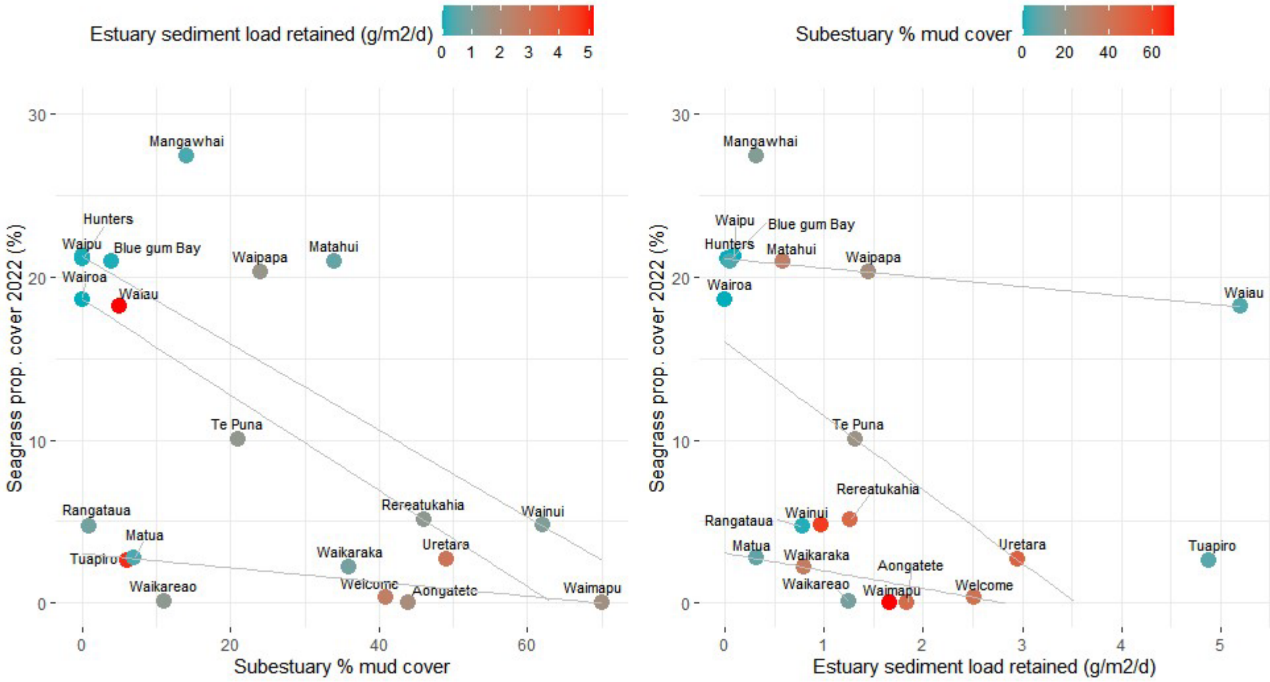

Figure 20 *Left: Seagrass cover (proportional to estuary size) against estuary % mud cover. The sites are identified by circles, and coloured dependant on sediment load retained in the estuary (g/m^2/d). Right: Seagrass cover (proportional to estuary size) against sediment load retained in the estuary (g/m^2/d). The sites are identified by circles, and coloured dependant on estuary mud proportion. Quantile regression lines (25th, 50th, and 75th percentile) are shown in light grey.*

Thresholds of sediment mud content have been previously reported in the literature, identifying a threshold of between 13% – 35% for seagrass presence (Park & Donald 1994, Zabarte-Maeztu et al. 2020, Flowers et al. 2023). An analysis of 69 sites monitored for seagrass cover and sediment characteristics in Tauranga Harbour identifies a strong threshold at approximately 30% mud content above which seagrass is rarely observed (Figure 21), a similar threshold to that seen in Figure 20, although based on aerial extent of percentage mud above 25%, rather than site specific mud content.

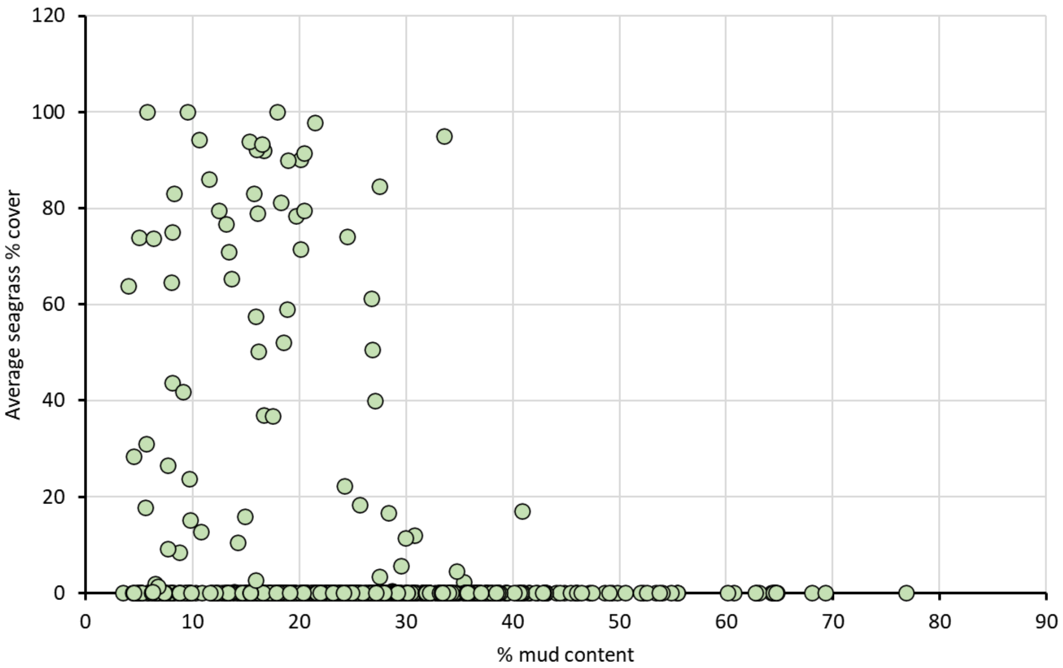

Figure 21 Average quadrat seagrass cover (%) and sediment percentage mud content at Tauranga Harbour NERMN estuary sites.

Table 14 Sub-estuaries in Tauranga Harbour identifying 2022 seagrass cover (hectares), proportional seagrass cover to estuary size, modelled SEDNET sediment loading from the catchment and retained in the estuary (Park et al. 2022), and modelled water column nutrient concentrations (Bryan & Stewart, 2022).

Subestuary	Seagrass cover (ha)	Seagrass cover/estuary area	Subestuary % mud cover	SEDNET contemporary catchment load (t/yr)	SEDNET contemporary estuary load (g/m^2/d)	NO_3 (g/m^3)	NH_4 (g/m^3)	PO_4 (g/m^3)	TN (g/m^3)
Waiau	18.54	18.2	5	3225	5.2	0.037	0.007	0.009	0.167
Tuapiro	6.60	2.6	6	6494	4.88	0.01	0.006	0.004	0.173
Uretara	7.15	2.7	49	3824	2.95	0.014	0.005	0.003	0.194
Rereatukahia	20.30	5.1	46	2421	1.26	0.015	0.005	0.003	0.232
Matahui	105.53	20.9	34	1631	0.58	0.043	0.009	0.01	0.45
Aongatete	0.09	0.02	44	4257	1.84	0.02	0.005	0.002	0.187
Wainui	32.33	4.8	62	1531	0.97	0.009	0.006	0.002	0.213
Waipapa	78.88	20.3	24	1715	1.45	0.019	0.007	0.003	0.222
Mangawhai	68.24	27.4	14	311	0.31	0.013	0.007	0.003	0.219
Te Puna	25.96	10.1	21	1436	1.31	0.017	0.007	0.004	0.215
Waikaraka	1.29	2.2	36	292	0.8	0.008	0.006	0.003	0.165
Matua	3.07	2.7	7	30	0.31	0.1	0.01	0.007	0.356
Waikareao	0.28	0.1	11	5135	1.25	0.167	0.014	0.008	0.353
Waimapu	0.01	0.006	70	6360	1.66	0.142	0.01	0.005	0.375
Welcome	0.60	0.4	41	1276	2.51	0.019	0.007	0.003	0.217
Rangataua	36.65	4.7	1	6527	0.78	0.033	0.008	0.003	0.246
Waipu	87.71	21.2	0	4	0.09	0.018	0.009	0.004	0.22
Hunters	205.90	21.1	0	39	0.03	0.011	0.007	0.003	0.207
Blue gum Bay	141.24	21.0	4	186	0.05	0.002	0.004	0.002	0.216
Wairoa	147.49	18.6	0	23910	0	0.115	0.012	0.007	0.382

4 Discussion/Matapakitanga

High resolution mapping of seagrass over time in estuaries across the Bay of Plenty has provided insights into broader trends of water quality and estuarine health. Recovery of seagrass is occurring in Tauranga Harbour, where significant expansion in extent has occurred, and in Maketū Estuary where it has returned in small patches following restoration of freshwater flows to the estuary. In contrast, three estuaries are showing ongoing degradation, including Ōhiwa Harbour, Waihī Estuary and Waioeka Estuary (Huntress Creek).

In Tauranga Harbour, the current seagrass coverage is linked to sediment grain size, with extensive cover rare above a threshold of approximately 30% mud content at a site, or when the spatial extent of muddy sediments exceeds 30% of estuary area. There is a clear relationship in sub-estuaries between lower catchment sediment loads and mud content, indicating the need to keep sediment runoff from the catchment as low as possible to protect and enhance seagrass abundance in the harbour. In practice, this requires ensuring sediment loads to the estuary are reduced through land management interventions in high-risk sediment loss zones. In addition, water clarity, which is linked to sediment loads, is crucial for health and growth of seagrass as it determines the amount of light that they receive while submerged. Analysis of the TSS data from all the significant monitored rivers and stream around Tauranga Harbour identify many having improving trends, and none having deteriorating trends. The estuary water quality data highlights the high variability in TSS concentrations recorded in the harbour. The impact of sediment and light on seagrass in the Bay of Plenty is covered in detail in Crawshaw *et al*. 2023 and indicates sedimentation can be one of the greatest stressors to seagrass. In the Tauranga Moana FMU there is 25,800 ha of land signed up with land management Environmental Plans (Figure 22) (excluding North Kaimai’s). Additionally, there has been 420 km of new fencing installed over the past five years. Results of monitoring of seagrass extents and water quality of the inflows points to the changes in planning policies, compliance activities and extensive land management improvements over the years achieving improvement of seagrass habitat requirements.

There is, however, another possible factor supporting seagrass return in Tauranga Harbour, the declining growth of sea lettuce (*Ulva* spp), which in recent years has had low coverage compared to historical distributions (Crawshaw 2021). The coverage of sea lettuce was best correlated to a model including the oceanic nino index (ONI), wind velocity, and sea lettuce tissue nutrients, indicating the interrelationships of climatic drivers and nutrient availability driving sea lettuce cover. Sea lettuce can smother seagrass, limiting light and causing loss of seagrass cover (see Crawshaw *et al.* 2023 for a detailed overview). As with TSS, trend analyses show that many tributaries to Tauranga Harbour are showing declining trends in nutrients, and only one an increasing trend, again suggesting that management interventions that reduce nutrient flux may be enhancing the habitat for seagrass growth.

In Maketū Estuary, restoration of freshwater flows from the Kaituna River has shown a range of positive improvements in estuary health. These include a significant reduction in the abundance of macroalgae which also reduces the prevalence of other stressors such as sulphides. Increased freshwater inflows have also reduced overall salinity of the estuary which increases seagrass tolerance to nitrogen stress. To date improvements in seagrass cover have not been evident, but this appears to need an improvement in substrate quality, which is likely to take time. The regrowth of several small patches of seagrass highlights the potential for further extent changes over time. Given that there have been changes to a number of environmental factors, it is not easy to isolate the key ones responsible for the current recovery.

For other estuaries in the Bay of Plenty, mapping indicates continued declining trends in Ōhiwa Harbour, Waihī Estuary and Waioeka Estuary. In Waihī Estuary, modelling has identified nutrients and sediment as the core drivers of decreased estuarine health, and a restoration plan needs to include nutrient and sediment reductions (Chakravarthy *et al*. 2021) and reducing the coverage of nuisance macroalgae through direct removal initiatives (DHI 2022). All of these estuaries are subject to the impacts of high catchment sediment loads. In particular the impact of large rainfall and sediment loads events causing high sediment deposition has been monitored in Waihī Estuary and Ōhiwa Harbour (Park, 2022, Crawshaw *et al*. 2023). These larger rainfall events can create large slugs of sediment, smothering seagrass and causing immediate loss. Further improvements are required in these estuaries to reverse the ongoing declines in seagrass cover.

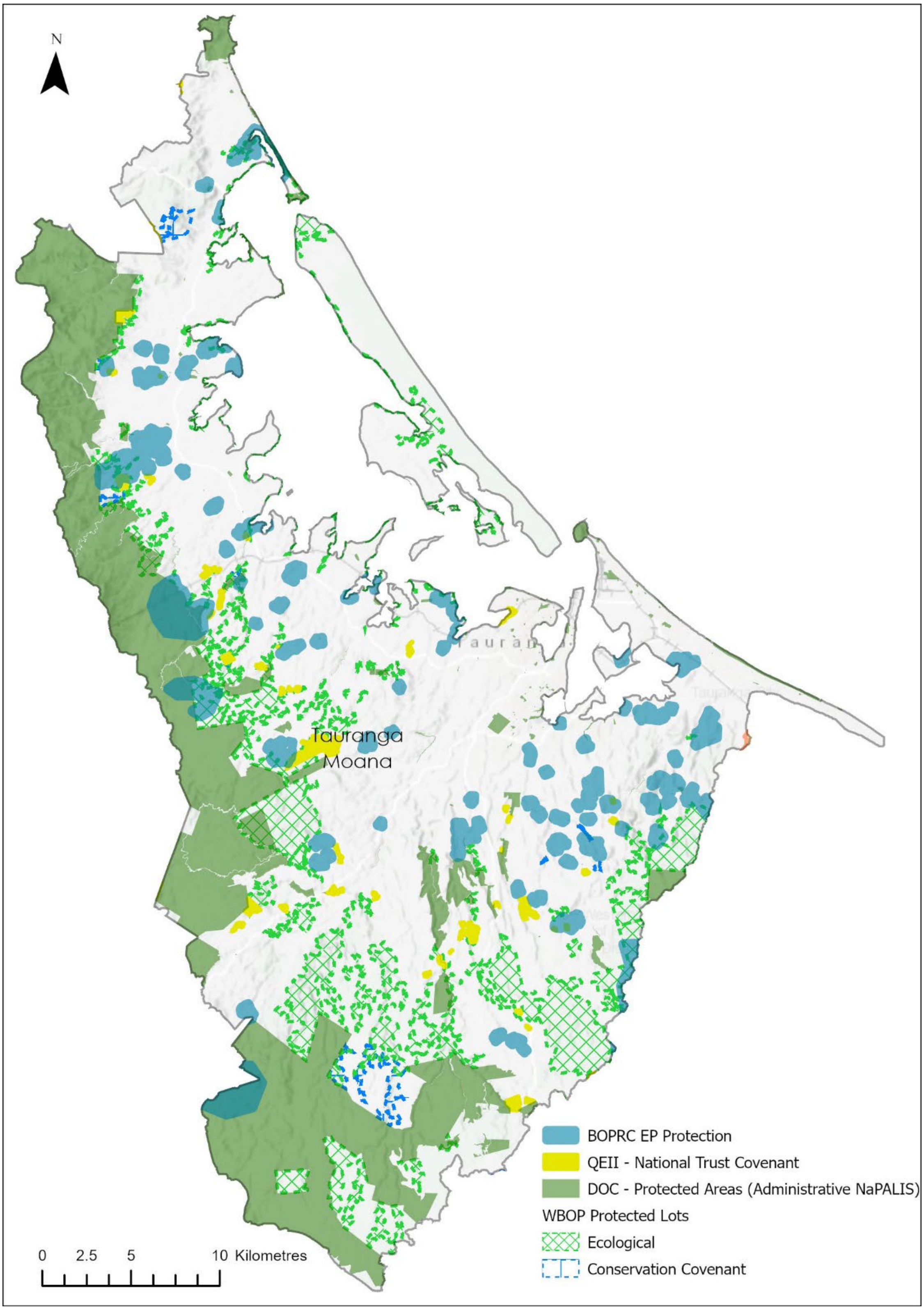

Figure 22 Tauranga Moana FMU with areas covered by BOPRC Environmental Programme protection in blue.

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Appendices/Ngā Āpitihanga

Appendix 1
Seagrass mapping protocol

Seagrass mapping protocol - NERMN

Spatial mapping of seagrass for the purpose of regional monitoring (NERMN) throughout the Bay of Plenty should be done every five years using the five-yearly supply of digital orthorectified aerial photography as a mosaicked RDAM with 25 cm pixel resolution. Currently mapping is done using manual techniques.

Mapping using GIS software shall have a defined attribute table using the classification parameters from previous extent mapping as held in our corporate SDE database. Parameters cover the appropriate hydrological and vegetative classes to ensure that the mapping can be included in any general biodiversity database or assessments.

To enable accurate comparison of seagrass extent change over time, polygons are mapped according to the cover or patchiness of the seagrass beds in an area (i.e. how much of the polygon is seagrass vs bare ground). Cover class classification is done using the Coastal and Marine Ecological Classification Standard (CMECS) to help align seagrass data collected nationally:

Coarse percent cover values	Cover class entry GIS
Trace or absent (<1%)	NA
Sparse (1 to <30%)	15
Moderate (30 to <70%)	50
Dense (70 to <90%)	80
Complete (90 to 100%)	95

Mapping is to be done at a minimum working scale of 1:500 but not more than 1:700 (i.e. usually 1:600) and the accuracy of the finished work will be suitable for publication at scales of 1:5,000 or greater. To provide guidance on the expected accuracy of the work the following should be followed:

- Where larger seagrass patches (1.5 m x 1.5 m or bigger) occur as isolated beds around 5 m or more from other seagrass patches they should be mapped as a polygon showing their extent and classified at 100% cover. If part of a loose aggregation/area of seagrass patches then map polygon tightly around perimeter of greatest extent excluding as much empty area as can be reasonably done and classify overall coverage accordingly.
- In large contiguous areas of seagrass patches at varying density the seagrass beds should be mapped to define areas of similar coverage as per the coverage classes. The minimum area of seagrass patches mapped by a polygon into a defined density class should be at least 25 m^2 (i.e. 5 m x 5 m) if within 5 m of larger patches or aggregations of small seagrass patches. Areas smaller than this will just be included into larger polygon areas with an appropriate overall density classification as above.
- Small seagrass patches down to 1 m x 1 m (1 m^2) are to be included in mapping where they occur as aggregations. However, if individual patches around 1 m^2 or less occur at distances of around 10 m or more from other seagrass, then they are not mapped at all.

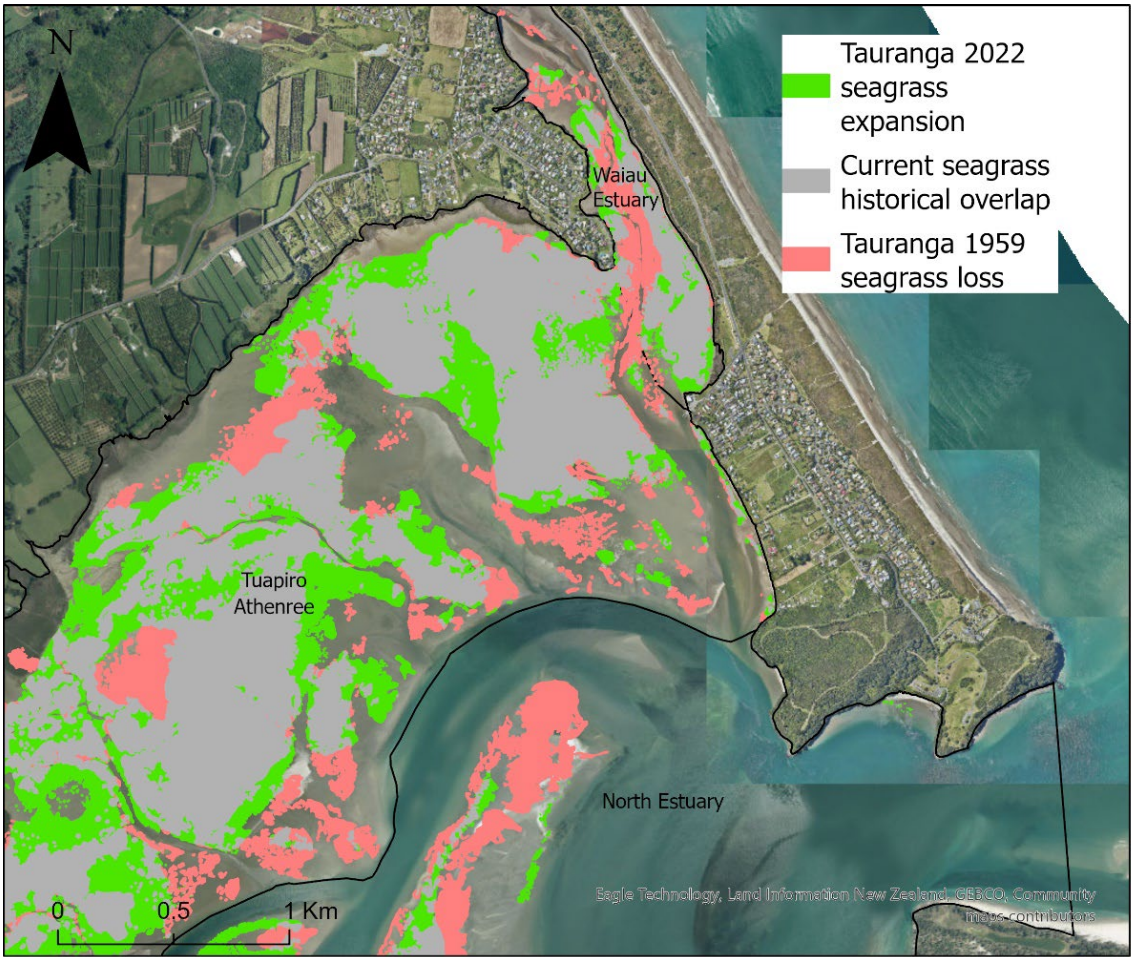
- In areas of small seagrass patches or larger patches that have low leaf density (and usually poor colour/contrast) which are hard to positively identify, ground truth verification should be made. Some coastal areas have 12.5 cm pixel resolution photography available and this can be used as a reference to help confirm whether seagrass is present.

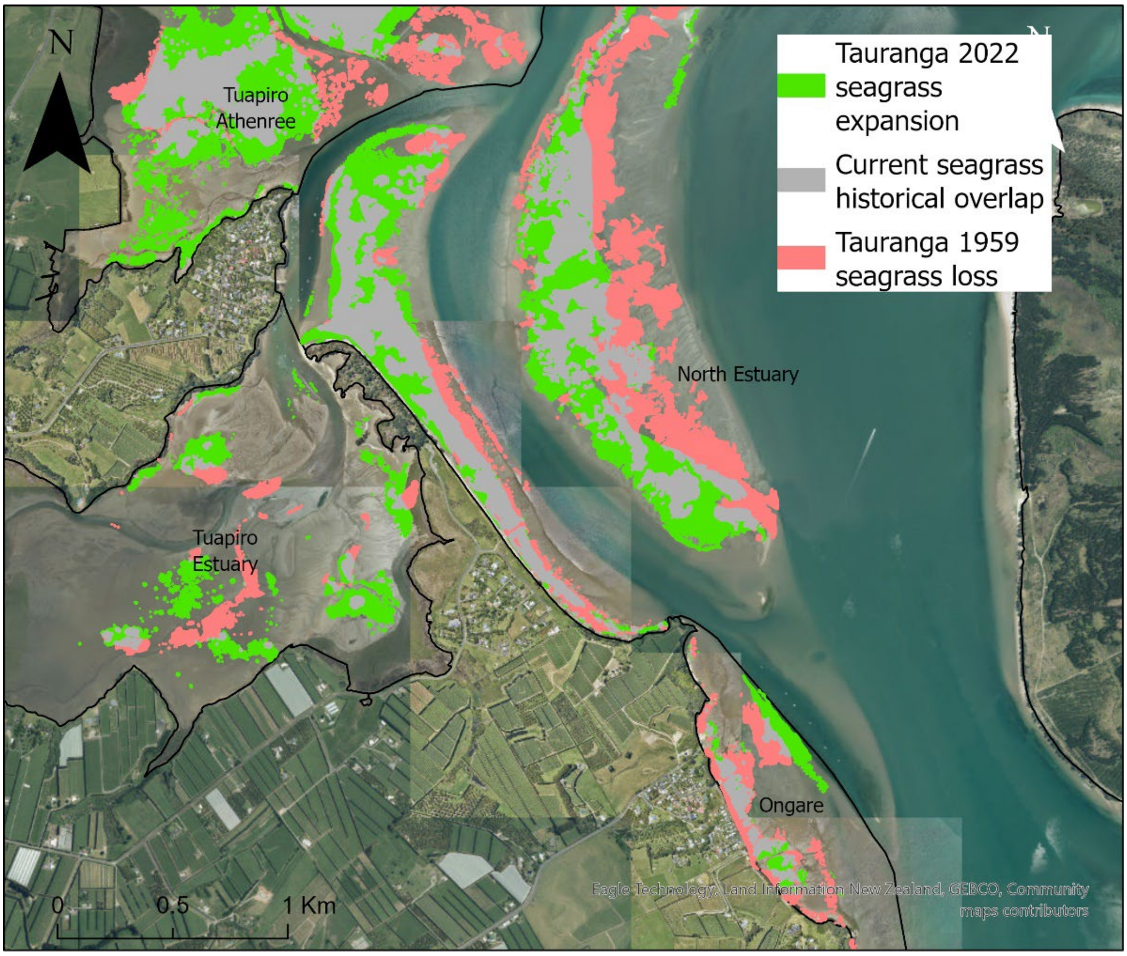
Seagrass coverage (classes/codes) is not based on the leaf density but rather the perimeter of the beds. Some beds may have numerous small patches inside the beds extent which has no seagrass present. In these cases, classify as per the overall average coverage. If the bare patches inside the seagrass beds are large (>5 m x 5 m) then they can be cut out of the polygon. However, if there are very numerous bare patches in a bed then it would be better just to classify as per the average overall coverage.

Classification of seagrass cover for 2011 and earlier

These cover classes are 0% - 40% (20%), 40% - 60% (50%), 60% - 90% (75%), 90% - 99% (95%) and 100%. The figures in brackets are the code used in attribute tables for the cover class entry.

Appendix 2
Tauranga Harbour sub-estuary level maps

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Current seagrass historical overlap
Tauranga 1959 seagrass loss
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North Estuary
Tuapiro Estuary
Ongare
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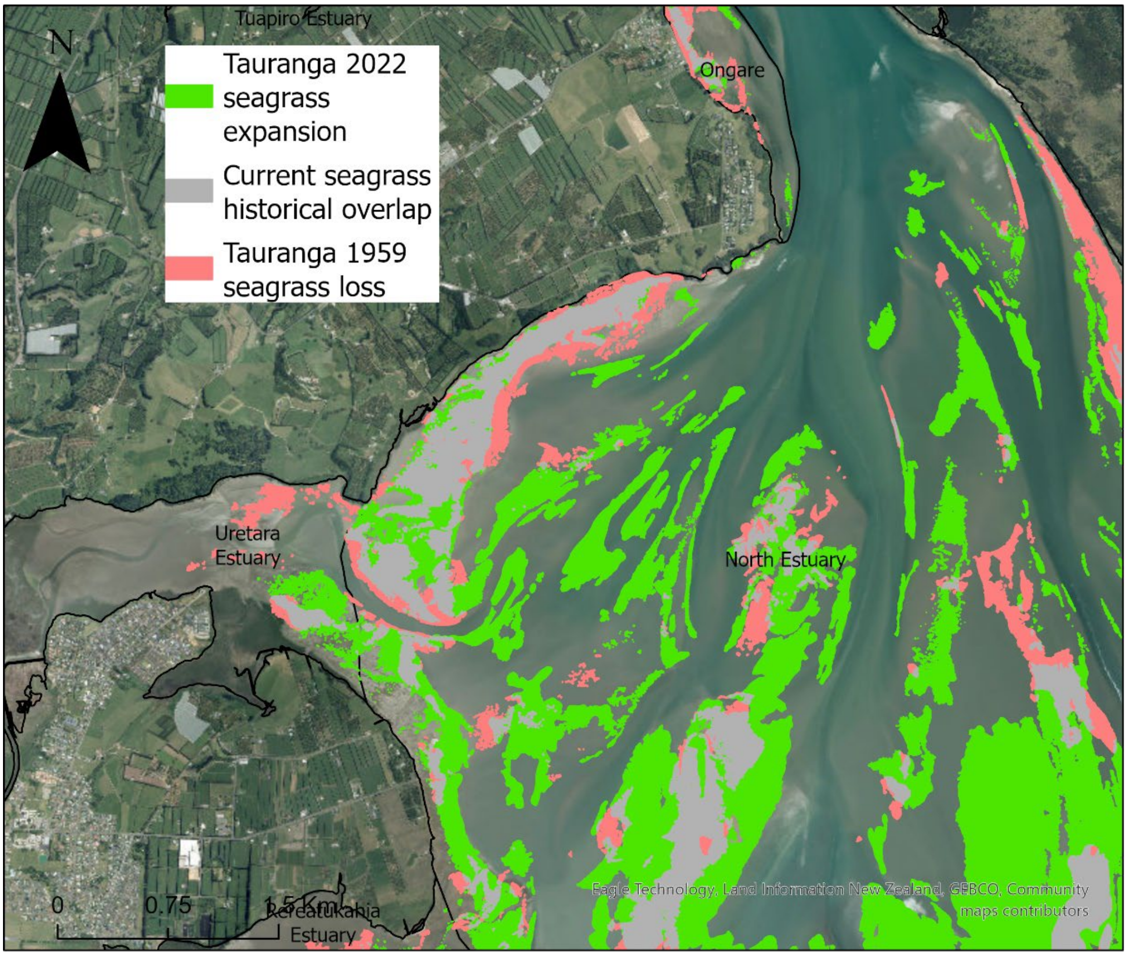
1 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors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Current seagrass historical overlap
Tauranga 1959 seagrass loss
Ongare
Uretara Estuary
North Estuary
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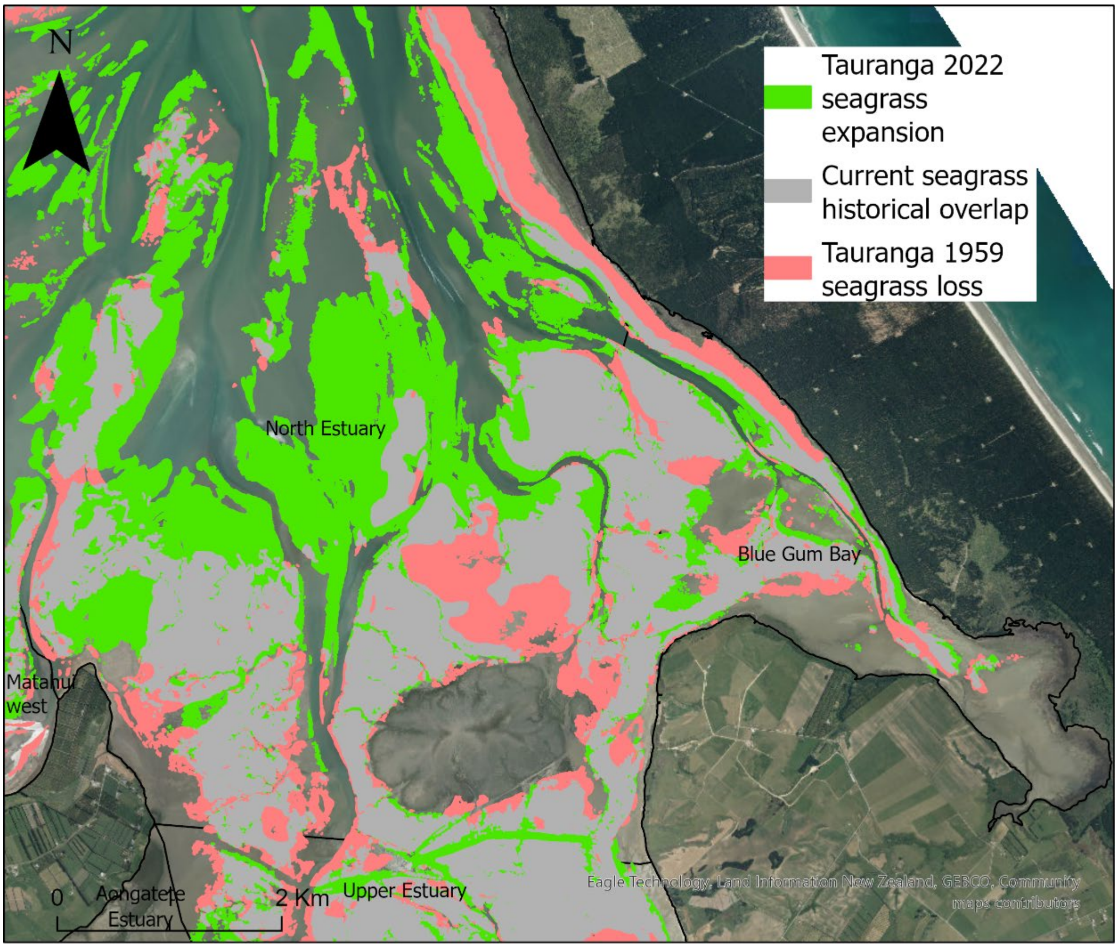
Kereatukahia Estuary
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors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Blue Gum Bay
Matahui west
Aongatete Estuary
Upper Estuary
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2 Km
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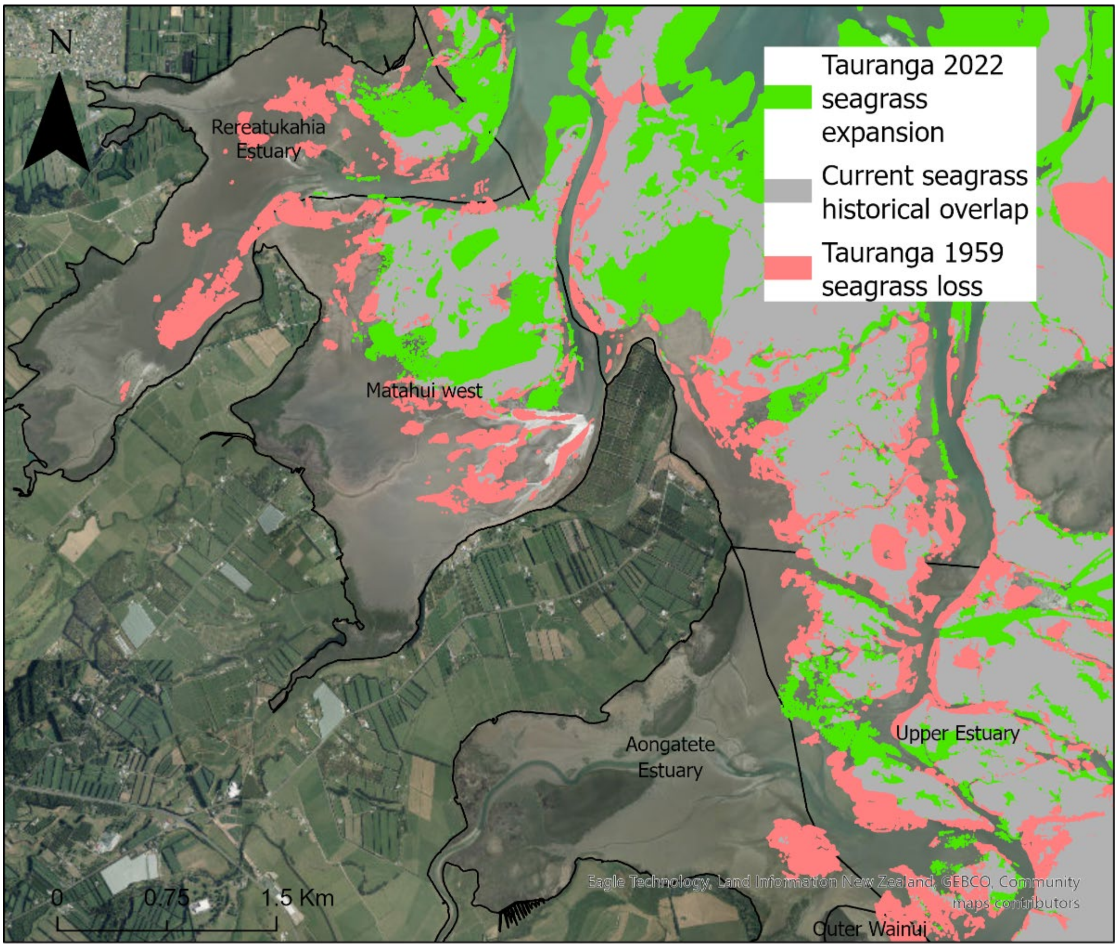
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Rereatukahia Estuary
Matahui west
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Upper Estuary
Outer Wainui
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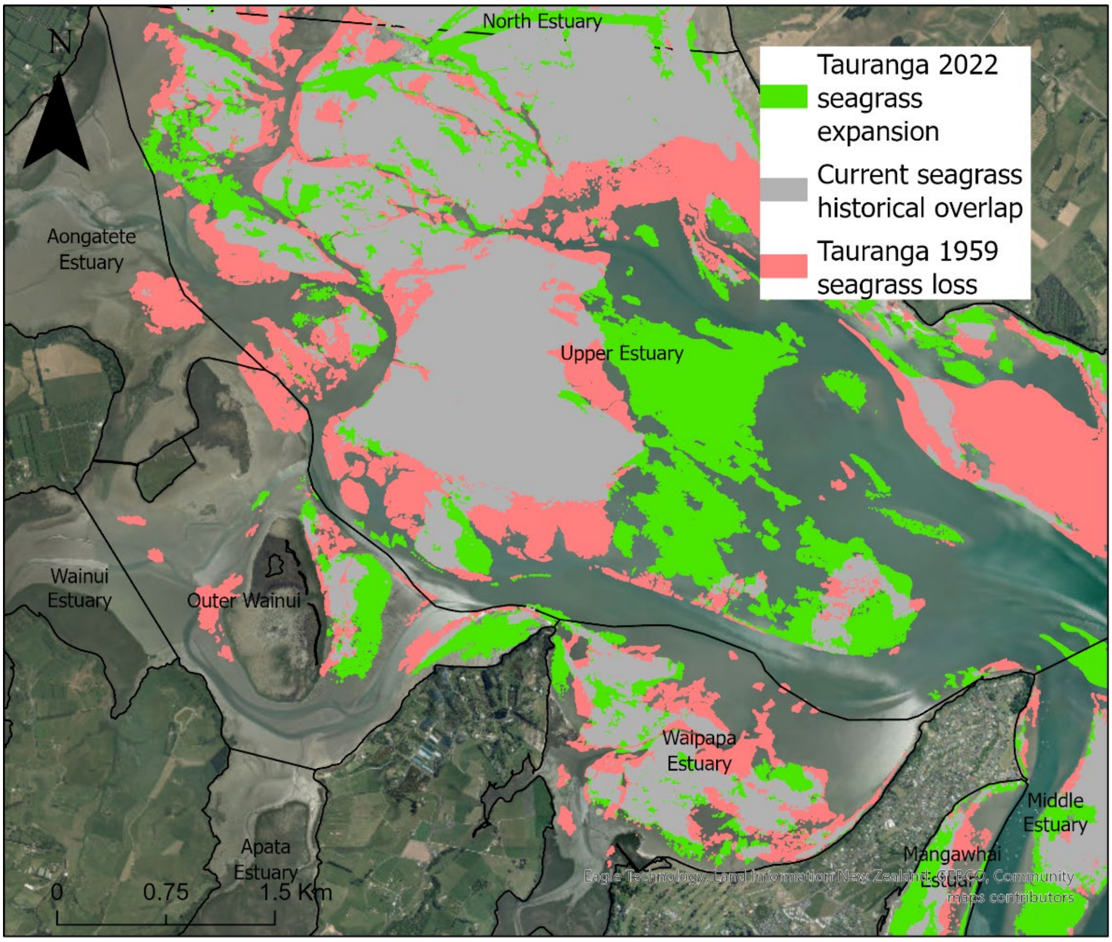
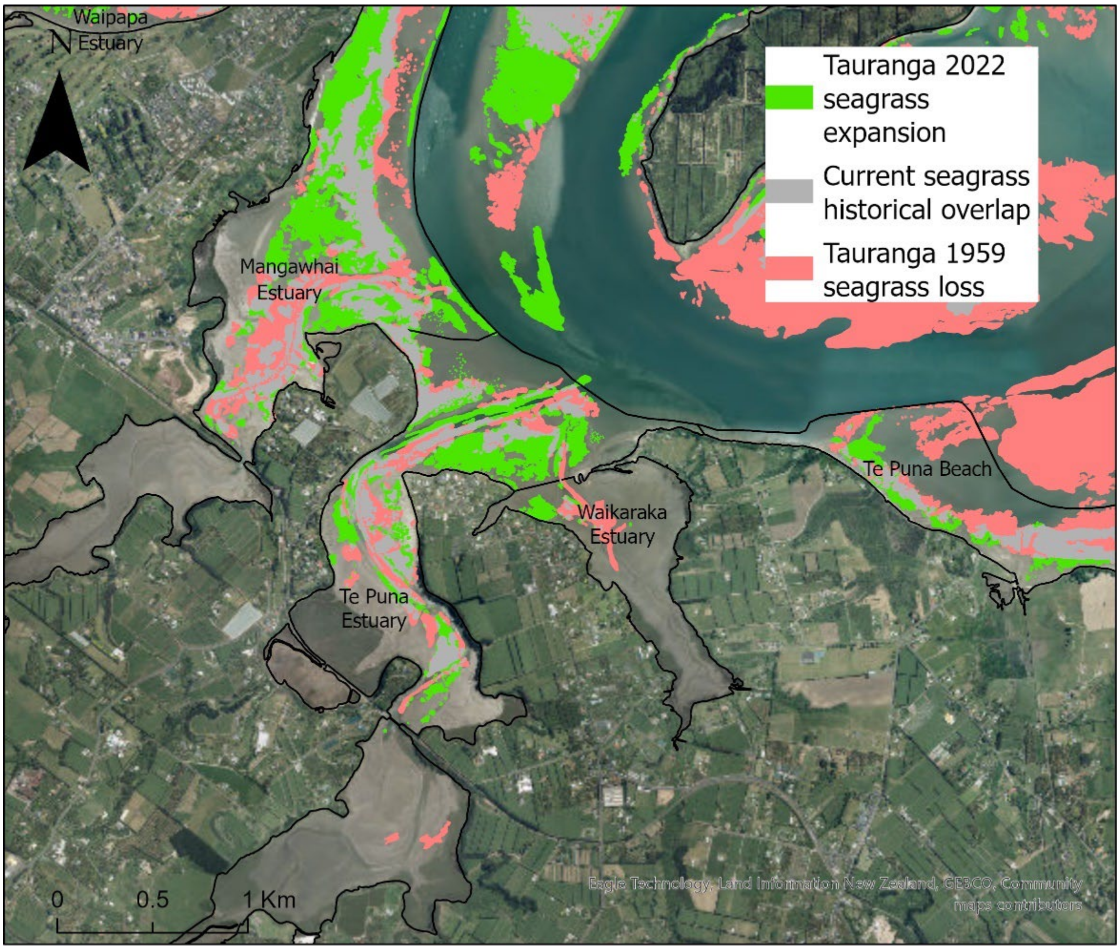
1.5 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors


North Estuary
Tauranga 2022 seagrass expansion
Current seagrass historical overlap
Tauranga 1959 seagrass loss
N
Aongatete Estuary
Upper Estuary
Wainui Estuary
Outer Wainui
Waipapa Estuary
Middle Estuary
Mangawhai Estuary
Apata Estuary
0
0.75
1.5 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors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Tauranga 1959 seagrass loss
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Te Puna Beach
Waikaraka Estuary
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1 Km
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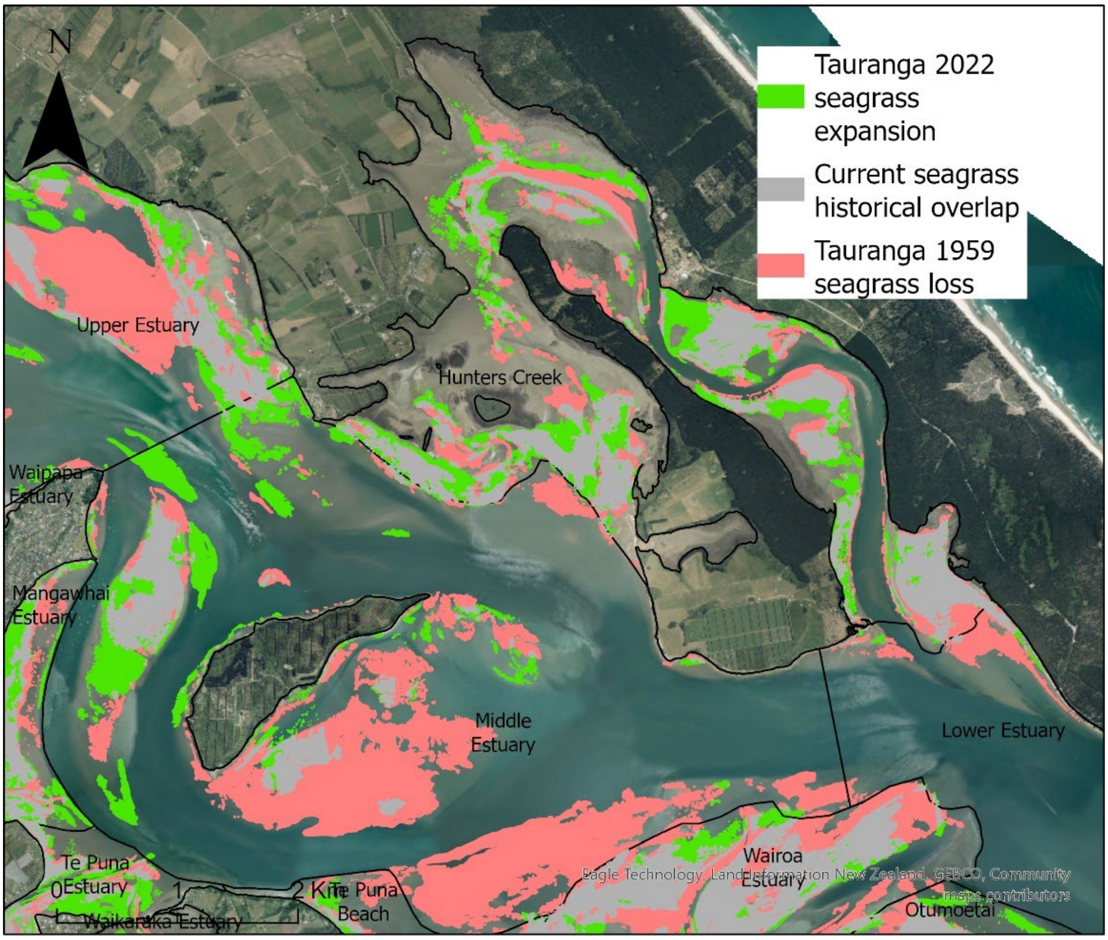
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Current seagrass historical overlap
Tauranga 1959 seagrass loss
Upper Estuary
Hunters Creek
Waipapa Estuary
Mangawhai Estuary
Middle Estuary
Lower Estuary
Te Puna Estuary
Waikaraka Estuary
Te Puna Beach
Wairoa Estuary
Otumoetai
0
1
2 Km
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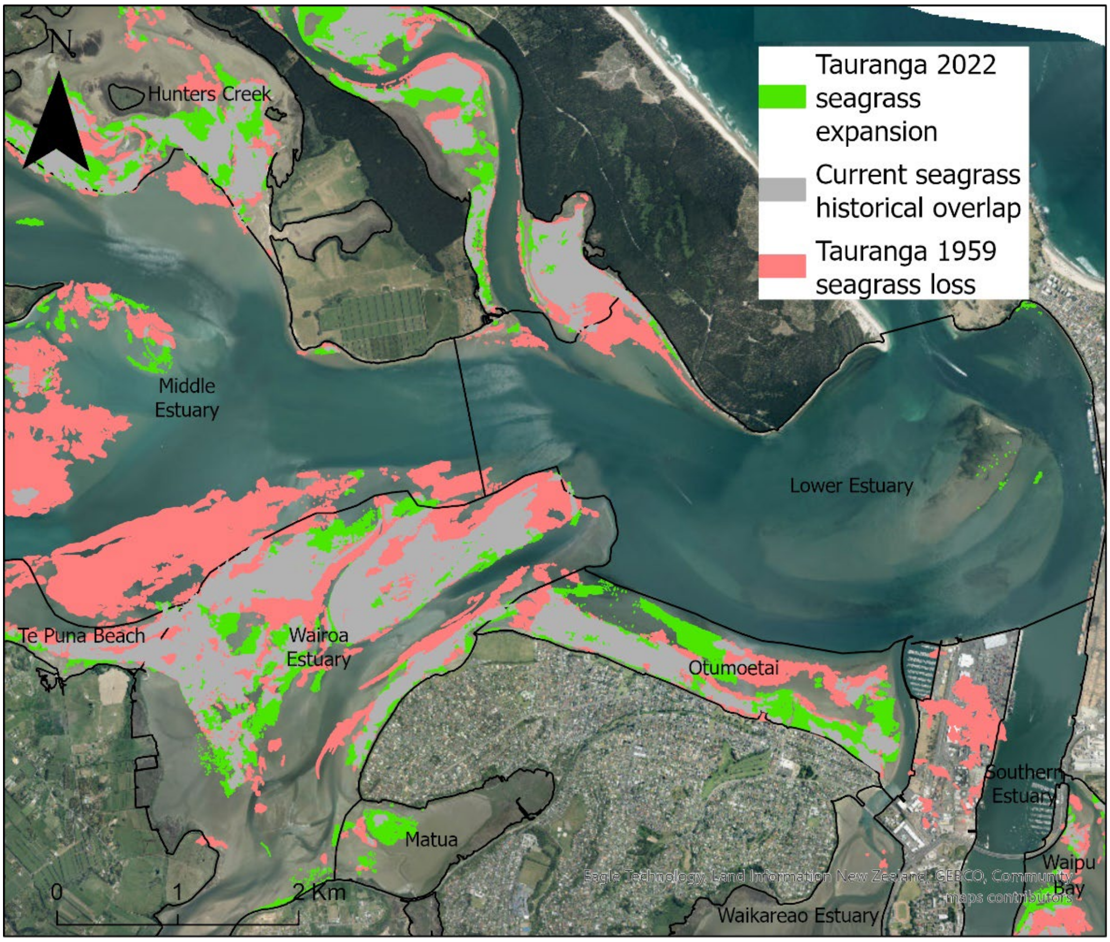
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Tauranga 1959 seagrass loss
Hunters Creek
Middle Estuary
Lower Estuary
Te Puna Beach
Wairoa Estuary
Otumoetai
Southern Estuary
Matua
Waipu Bay
Waikareao Estuary
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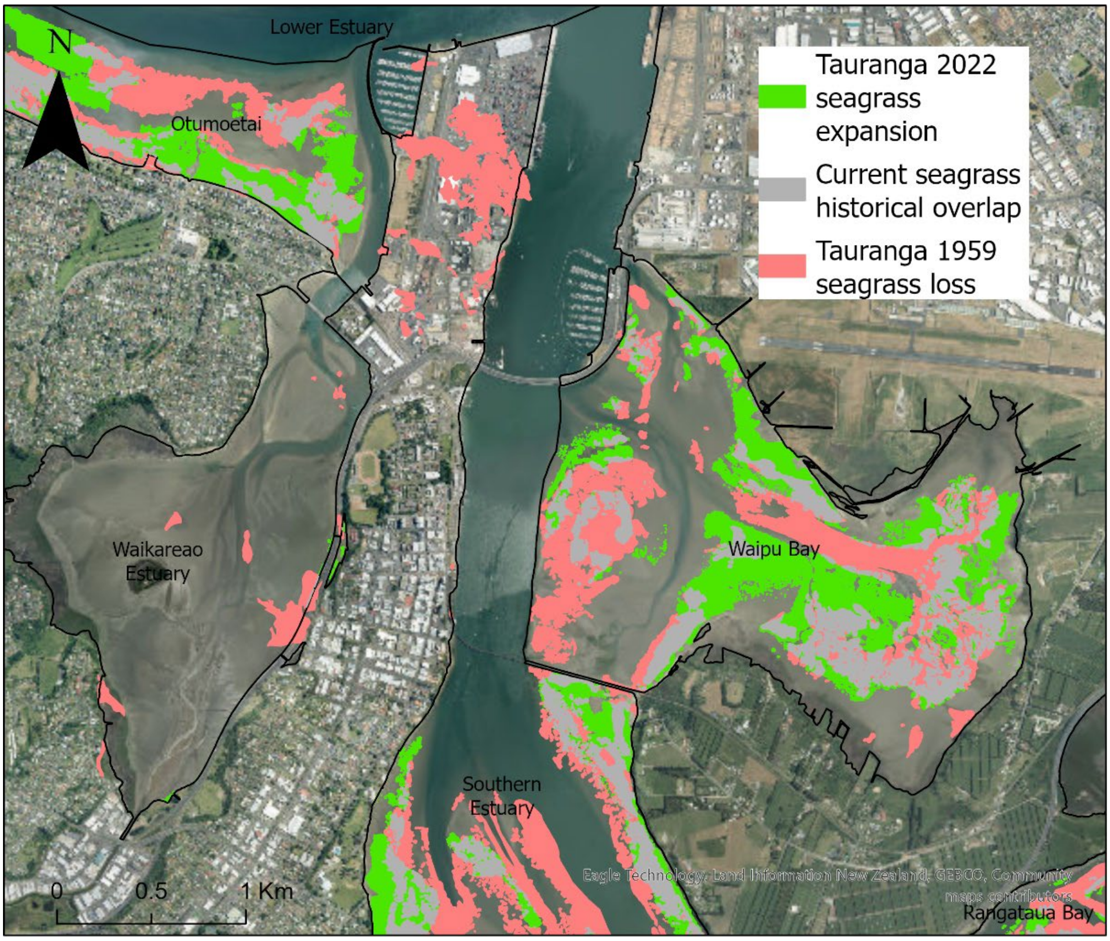
1
2 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors


Lower Estuary
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Otumoetai
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Southern Estuary
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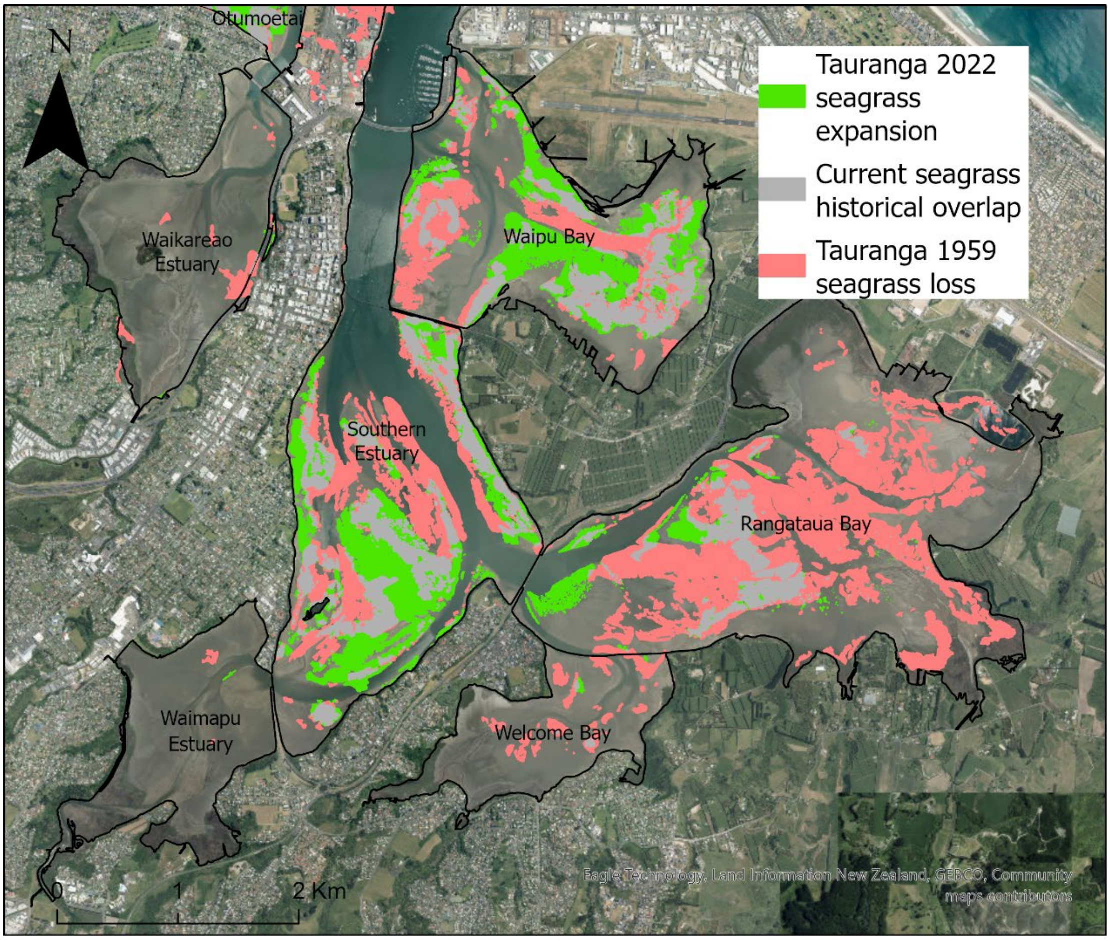
0.5
1 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors
Rangataua Bay


Otumoetai
N
Tauranga 2022 seagrass expansion
Current seagrass historical overlap
Tauranga 1959 seagrass loss
Waikareao Estuary
Waipu Bay
Southern Estuary
Rangataua Bay
Waimapu Estuary
Welcome Bay
0
1
2 Km
Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors

Appendix 3
Tauranga Harbour catchment water quality trends

Table 15 Nitrate/nitrite linear regression results for Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	Median	R	Slope	Prob	change/year
Waiau	155	0.249	0.137	0.00001	0.090	0.00365
Tuapiro	157	0.078	0.089	0.000002	0.268	0.00073
Uretara	198	0.187	0.031	0.000002	0.669	0.00073
Rereatukahia	220	0.32	0.110	0.000002	0.104	0.00073
Te Mania	308	0.258	0.142	0.000009	0.013	0.003285
Waitekohe	238	0.083	0.035	0.000001	0.590	0.000365
Aongatete	163	0.243	0.078	0.000004	0.324	0.00146
Waipapa	195	0.516	0.124	-0.000007	0.085	-0.00256
Omanawa	319	1.09	0.677	0.00004	0.000	0.01460
Kopurererua	285	0.921	0.376	0.00002	0.000	0.00730
Waimapu	251	0.758	0.140	0.000008	0.027	0.00292
Waitao	234	0.447	0.280	-0.00002	0.000	-0.0073
Rocky	200	0.734	0.338	-0.00004	0.000	-0.0146

Table 16 Total nitrogen linear regression results for Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	Median	R	Slope	Prob	change/year
Waiau	150	0.335	0.087	0.00001	0.288	0.00365
Tuapiro	154	0.1555	0.138	-0.000005	0.088	-0.00183
Uretara	197	0.261	0.122	-0.000006	0.089	-0.00219
Rereatukahia	218	0.398	0.047	-0.000006	0.492	-0.00219
Te Mania	306	0.42	0.014	0.000001	0.811	0.000365
Waitekohe	239	0.17	0.161	-0.000009	0.013	-0.00329
Aongatete	163	0.331	0.040	-0.000002	0.608	-0.00073
Waipapa	194	0.615	0.228	-0.00001	0.001	-0.00365
Omanawa	306	1.21	0.596	0.00003	0.000	0.01095
Kopurererua	286	1.061	0.188	0.00001	0.001	0.00329
Waimapu	250	0.931	0.025	0.000002	0.594	0.00073
Waitao	234	0.608	0.456	-0.00003	0.000	-0.01095
Rocky	199	1.23	0.367	-0.00007	0.000	-0.02555

Table 17 Total Suspended Solids (log10x+1) linear regression results for Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	Median	R	Slope	Prob	change/year
Waiau	155	0.5	0.02	0.000003	0.803	0.001095
Tuapiro	161	0.3	0.042	-0.000004	0.593	-0.00146
Uretara	184	0.329	0.167	-0.00002	0.023	-0.0073
Rereatukahia	219	0.3	0.079	-0.00002	0.247	-0.0073
Te Mania	310	0.8	0.161	-0.00002	0.005	-0.0073
Waitekohe	242	0.3	0.107	-0.00001	0.098	-0.00365
Aongatete	162	0.3	0.072	0.000007	0.365	0.002555
Waipapa	195	0.38	0.024	0.000002	0.744	0.00073
Omanawa	326	1.1	0.087	-0.000007	0.117	-0.00256
Kopurererua	320	1.2304	0.152	-0.00002	0.005	-0.0073
Waimapu	256	0.903	0.008	0.0000008	0.901	0.000292
Waitao	237	0.845	0.027	0.000002	0.682	0.00073
Rocky	201	0.7482	0.070	0.00001	0.322	0.00365

Table 18 Nitrate/nitrite linear regression results for flow adjusted Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	R	Slope	Prob	change/year	% change/year
Waiau	125	0.023	-0.0000009	0.798	-0.00033	-0.13193
Tuapiro	132	0.090	-0.000002	0.304	-0.00073	-0.9359
Uretara	160	0.083	-0.000003	0.299	-0.0011	-0.58556
Rereatukahia	154	0.042	-0.000006	0.607	-0.00219	-0.68438
Te Mania	259	0.058	0.000002	0.353	0.00073	0.282946
Waitekohe	186	0.064	-0.000002	0.382	-0.00073	-0.87952
Aongatete	122	0.098	-0.000005	0.285	-0.00183	-0.75103
Waipapa	141	0.380	-0.00002	0.000	-0.0073	-1.41473
Omanawa	na	na	na	na	na	na
Kopurererua	na	na	na	na	na	na
Waimapu	224	0.058	-0.000007	0.385	-0.00256	-0.33707
Waitao	185	0.411	-0.00003	0.000	-0.01095	-2.44966
Rocky	172	0.403	-0.00005	0.000	-0.01825	-2.48638

Table 19 Total Nitrogen linear regression results for flow adjusted Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	R	Slope	Prob	change/year	% change/year
Waiau	120	0.256	-0.000006	0.005	-0.00219	-0.65373
Tuapiro	131	0.368	-0.000002	0.000	-0.00073	-0.46945
Uretara	159	0.399	-0.00002	0.000	-0.0073	-2.79693
Rereatukahia	150	0.395	-0.00002	0.000	-0.0073	-1.83417
Te Mania	259	0.196	-0.00001	0.001	-0.00365	-0.86905
Waitekohe	187	0.270	-0.00002	0.000	-0.0073	-4.29412
Aongatete	122	0.216	-0.00001	0.017	-0.00365	-1.10272
Waipapa	141	0.436	-0.00002	0.000	-0.0073	-1.18699
Omanawa	na	na	na	na	na	na
Kopurererua	na	na	na	na	na	na
Waimapu	223	0.204	-0.00002	0.002	-0.0073	-0.7841
Waitao	171	0.423	-0.00002	0.000	-0.0073	-1.20066
Rocky	169	0.576	-0.00009	0.000	-0.03285	-2.67073

Table 20 TSS (log10 x+1) linear regression results for flow adjusted Tauranga Harbour River monitoring data from 1990 – 2023.

River	N	R	Slope	Prob	change/year	% change/year
Waiau	124	0.217	-0.00001	0.015	-0.00365	-0.38706
Tuapiro	135	0.203	-0.00001	0.018	-0.00365	-0.84091
Uretara	169	0.352	-0.00004	0.000	-0.0146	-2.91771
Rereatukahia	169	0.231	-0.00004	0.002	-0.0146	-3.32163
Te Mania	270	0.306	-0.00004	0.000	-0.0146	-0.62263
Waitekohe	191	0.134	-0.00001	0.065	-0.00365	-0.84091
Aongatete	124	0.158	-0.000008	0.080	-0.00292	-0.67329
Waipapa	153	0.264	-0.00002	0.001	-0.0073	-1.19159
Omanawa	285	0.135	-0.00001	0.022	-0.00365	-0.07222
Kopurererua	304	0.355	-0.00002	0.000	-0.0073	-0.10419
Waimapu	242	0.241	-0.00002	0.000	-0.0073	-0.23818
Waitao	185	0.169	-0.00001	0.022	-0.00365	-0.13952
Rocky	178	0.041	0.000006	0.587	0.00219	0.109896