Monitoring coastal suspended sediment in Aotearoa New Zealand: utility of satellite remote sensing

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Cover image: *Pseudo-true colour MODIS-Aqua images of lower North Island, New Zealand [17 January 2004 (left) and 25 February 2004 (right)], illustrating changes in coastal suspended sediment from after a stormflow event. [Images: Courtesy of NASA, prepared by Matt Pinkerton, NIWA]*

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Executive summary

There is concern about the ecological and environmental effects of suspended sediment input in the Aotearoa New Zealand coastal marine area (CMA). This report, commissioned by the Department of Conservation as part of their "Reducing Coastal Sediment Impacts" project, provides guidance on the utility of satellite remote sensing for monitoring suspended sediment and its effects on water clarity.

Satellite long-term trends and regional interpretation (2002-2021)

The report presents an analysis of trends in the concentration of Total Suspended Solids (TSS) in the New Zealand coastal zone 2002-2021 from monthly MODIS-Aqua satellite images. Seasonality was removed, but residual effects of climate cycles can still affect these linear trends and within-season trends (e.g. trends in a given month or in a given season such as summer) can be different to the overall (annual-scale) linear trend.

In general, we found *increasing* trends in TSS concentrations (> 3 mg m^{-3} yr^{-1}, about +0.3 %/y) around coastal regions of the South Island, while most of the North Island has *decreasing* trends (< 3 mg m^{-3} yr^{-1}). The drivers of these broad-scale trends are not well known, but are likely to result from a combination of: (1) changes in phytoplankton-derived particulates (climate- and nutrient-driven variations in primary production); (2) changes to oceanographic conditions which influence coastal erosion and resuspension of benthic sediment (e.g. wave climate); (3) changes to inputs of suspended sediment from the land. On finer spatial scales, patterns of long-term change in TSS close to some estuary and river mouths (both increasing and decreasing trends) strongly suggest decadal changes to terrestrial (riverine) input of TSS to the coastal zone are responsible. The locations where changes to TSS over this period are likely related to changes in the riverine supply of suspended sediment are identified in the report in Section 6.4.

Case studies

Considerable global resources are committed to maintaining and developing the Earth-observation network, especially in USA and Europe, and many satellite products are provided on a "no-cost basis" to the user. Remote sensing case studies in New Zealand show that these free satellite data have provided insights into patterns and changes in TSS and/or water clarity in several important areas including Canterbury Bight, Akaroa Harbour, Lyttelton Harbour, South Taranaki Bight, Manukau Harbour, west coast Waikato and Wellington Harbour. The satellite data have been used in New Zealand and overseas to show spatial and seasonal patterns in TSS, water clarity and productivity, estimate background conditions for environmental impact assessments, track change, model habitat suitability for cetaceans, and demonstrate coastal connectivity (e.g. where sediment is released from one estuary and tracks into another).

Conclusions and recommendations

Detailed recommendations to improve the value of satellite remote sensing over the next 1–5 years are presented in Section 7 and these should be read alongside Green et al. (2021)[1]. Feedback from three stakeholder engagement workshops were used to guide these conclusions and recommendations. In particular, there was much discussion at the workshops on the difference between TSS (as observed by the satellites) and "sediment" (often taken to mean the supply of sediment to the CMA from rivers and estuaries). Satellite TSS data include sediment from

[1] *"Steering our waka through turbid waters: Research priorities over the next 5 years for sediment in the coastal marine area of Aotearoa New Zealand"*

rivers/estuaries, from coastal erosion and resuspended from the seabed, but does not include bedload[2]. The workshops also discussed that sediment supply to the coastal environment is profoundly episodic, for example due to flood events and coastal storms, and that satellite data are poor at capturing these short-term events.

The workshops and case studies show that satellite observation, *in situ* and modelling methods are complementary: satellite data are not the "silver bullet". Instead, a variety of *in situ* monitoring and research is needed to improve knowledge and understanding of suspended sediment in the CMA: satellite data should be used alongside *in situ* sampling (regular water collections, lab analysis), autonomous instrumentation (moorings, gliders, cameras) and modelling. The best insights will be achieved by using multiple methods together.

Based on the 16 detailed recommendations given in the report, our "top" recommendations are:

1. **Co-ordinate and improve *in situ* TSS monitoring**: We recommend improving methods to connect *in situ* monitoring to remote sensing data. The usefulness of regular (e.g., monthly) monitoring of sediment (TSS) at coastal sites would be improved by measuring attenuation and optical backscatter at the same time and same location as taking the water sample. Secchi depth and beam transmissometers should be used to measure attenuation at monitoring sites. Turbidity can be used as a proxy for optical backscatter but because different turbidity sensors approximate optical backscatter in different ways, co-ordination/standardisation, better calibration and improved characterisation of turbidity sensors used by different agencies is needed.

2. **Develop pilot studies of new satellite capability**: Satellite data relevant to coastal sediment are available at moderate resolution (100s of metres) and go back to 2002 (NIWA-SCENZ[3]). More recently, high-spatial resolution (1–10s of metres) satellite data are available and provide information on sediment in smaller estuaries, harbours, fiords, and lakes. Both resolutions of satellite data are currently under-used in New Zealand. We recommend that the national-scale TSS trend analysis presented here be used to select priority areas for pilot studies to explore the utility of the new satellite capability for monitoring coastal sediment. This includes continued development of NIWA-SCENZ. A "sceptical early-adopter" mindset is recommended: scientists and managers should actively seek new applications of these satellite data whilst developing an awareness of limitations.

3. **Improve *in situ* monitoring of sediment in rivers and estuaries**: Radiometric sensors ("camera like" instruments sensors that measure the colour of water) can provide estimates of TSS concentration using methods similar to those used in satellite processing. These could be mounted from high vantage points and/or bridges to provide near-continuous (during daylight) information on TSS in rivers and estuaries. We recommend exploring whether this radiometric approach could deliver a cost-effective way of monitoring the input of suspended sediment to the CMA. These radiometric sensors could potentially be used in conjunction with continuous *in situ* monitoring (e.g., turbidity sensors in rivers or on moorings).

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[2] Bedload: coarse particles, including sand, which roll, slide or saltate on or close to the riverbed

[3] NIWA-SCENZ: Seas, Coasts, Estuaries New Zealand. Available at: https://data-niwa.opendata.arcgis.com/documents/NIWA::niwa-scenz-ocean-colour-application/explore

1 Introduction

1.1 Context for this report

The Department of Conservation (DOC) advocates for conservation values (a Conservation Act function of the Department) through Resource Management Act (RMA) processes, and supports the Minister of Conservation's coastal management functions including the New Zealand Coastal Policy Statement (NZCPS). In 2018, DOC produced specific NZCPS guidance[4] for sedimentation and wrote a review report to the Minister of Conservation on the effects of the NZCPS-2010 on RMA decision-making. In this review, sedimentation was highlighted as an issue of ongoing concern[5].

More recently, DOC received funding from Budget 2018 for researching key threats to marine habitats which are managed under the RMA (within 12 nm boundary). Based on the rankings of MacDiarmid et al. (2013), marine sedimentation was chosen for this project as the highest ranked marine pressure that can be mitigated under the RMA (NZCPS Policy 22), e.g. through management of land-derived sediments, and marine based activities, under regional policies, plans and consents. Specifically in terms of sedimentation, local authorities must give effect to NZCPS Policy 22:

1. Assess and monitor sedimentation levels and impacts on the coastal environment.
2. Require that subdivision, use, or development will not result in a significant increase in sedimentation in the coastal marine area, or other coastal water.
3. Reduce sediment loadings in runoff and in stormwater systems through controls on land use activities.

Monitoring suspended sediment is also recognised as being an important part of a National Marine Environment Monitoring Programme (MEMP) for Aotearoa New Zealand (Hewitt et al., 2014; PCE, 2019).

1.2 Overall objective

The overall objective of the present project is to present national trends in coastal water sediment using satellite images and assess the utility of satellite imagery and other tools for coastal and marine sediment management, through a desk top exercise and stakeholder engagement.

1.3 Specific Objectives

This project has three sets of specific objectives:

1.3.1 A national spatial assessment of long-term trends in coastal sediment.

- Using satellite data behind NIWA-SCENZ to identify the key places of change, over 18 years, in suspended sediment (including concentration and water clarity) and their physical characteristics; e.g. river mouths and other coastal areas, and exposed versus sheltered locations.

[4] https://www.doc.govt.nz/about-us/science-publications/conservation-publications/marine-and-coastal/new-zealand-coastal-policy-statement/policy-statement-and-guidance/
[5] https://www.doc.govt.nz/about-us/science-publications/conservation-publications/marine-and-coastal/new-zealand-coastal-policy-statement/

- Assess how satellite-derived TSS estimates relate to inputs derived from the Ministry for the Environment's 2019 sediment load estimator.[6]
- Preliminary assessment of the causes of observed long-term changes in suspended sediment.
- Recommend further analysis to link the results to potential reasons for the observed changes; e.g.:
  - Comparison with the Landcover Database - LCDB v5.0 summer 1996/97, summer 2001/02, summer 2008/09, summer 2012/13, and summer 2018/19[7].
  - The climate change setting; e.g. extreme rainfall events & droughts.
  - Data from the MfE SoE reporting, LAWA, and river quality monitoring network.

1.3.2 Observation techniques for coastal sedimentation

- An overview of tools and techniques to observe coastal sediment.
  - Remotely sensed imagery including via NIWA-SCENZ, gliders, drones, continuous monitoring buoys, satellite models, coastal cameras/webcams.
  - Including detailed caveats and limitations of each of the tools; e.g. satellite imagery cannot detect sediments at depth and is limited by cloud cover during and after storm events.
  - A literature review of how various techniques have been used in Aotearoa New Zealand and overseas, and with what management success, including level of investment.
- Presenting options for future work and approximate resources required.
  - New tool development and refinements to existing tools to better inform knowledge and management of sediments.
  - How tools can be used in conjunction with each other; e.g. ground-truthing satellite images with on the ground consent data, incorporating satellite data with wave energy data to understand contribution of natural resuspension, and linking satellite data with river monitoring data.
  - How tools can be used to inform a range of management issues; e.g. threatened species recovery (penguin foraging areas), management for marine protected areas, impacts from large events (landslides, fires) and activities (dredging, sandmining, coastal development and other land-use changes).
  - An expert opinion on how the observation technology and analysis science will develop in the next 5 years (an international 'horizon scan').

[6] https://www.mfe.govt.nz/publications/fresh-water/updated-sediment-load-estimator-new-zealand
[7] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

1.3.3 Engagement

- Present and receive feedback via online meetings, for 2 hours each, with management agencies. Any actions from meetings to be agreed with the contract supervisor via email.
  - Two meetings to refine the project plan (May/June).
  - Two meetings to discuss and assess progress and seek input on the first drafts (July - December).

1.4 Out of Scope

Detailed analysis of the causes of any trends observed e.g. comparison with other datasets such as LCDB versions.

1.5 Report outline

Section 2 provides an overview of the ecological and environmental effects of suspended sediment and potential for sedimentation, and a conceptual (high-level) initial summary of where satellite remote sensing fits into the bigger picture of suspended sediment research in New Zealand. Section 3 introduces the current (state-of-the-art) capability in satellite remote sensing of suspended particulate material, including its key strengths and limitations. Section 4 discusses *in situ* instrumentation (above-surface and immersed) in relation to how they can be used in conjunction with satellite methods. Section 5 presents some recent case studies using satellite data for sediment-related questions around New Zealand. Section 6 provides a national-scale assessment of recent, long-term (2002-2020) trends in total suspended solids concentrations in the New Zealand coastal marine area. Section 7 provides recommendations for future work on developing and applying satellite data for suspended sediment applications. Appendix A gives details and examples of the use of the NIWA NIWA-SCENZ tool (a portal to explore 20-years of moderate-resolution satellite data for New Zealand). Appendix B give a summary of the user-engagement workshops held as part of this project.

2 Overview of sediment effects in coastal waters

2.1 Ecological and environmental effects of suspended sediment and sedimentation

On rocky coasts, studies of ecological problems caused by sedimentation[8] are widespread, have a long history, and are increasing globally acknowledged (Airoldi, 2003). Sedimentation can also adversely affect soft sediment ecosystems. After some early studies (McKnight 1969; Peterson 1985) there has been considerable recent research in New Zealand (and overseas) showing the potential for substantial impacts associated with smothering by terrestrial sediment deposits (e.g., Miller et al., 2002; Ellis et al., 2004; Lohrer et al., 2004). Many of the key papers were used to develop ANZECC[9] guidelines for estuary sedimentation (Townsend & Lohrer, 2015) and recommendations for DOC research priorities for sediments in the CMA (part of Green et al., 2021). As well as potential effects of its deposition, and its effect on filter-feeding organisms in the water column, suspended sediment increases the attenuation of light (i.e. changes water clarity). Fine particulate material on the seabed is available to be resuspended if the combined action of waves and currents is sufficient, so that there is a dynamic interchange between suspended sediment and sedimentation.

In New Zealand as in other parts of the world, the focus has been on the environmental effects of sediment based on mass concentrations (e.g., Hughes et al., 2015). However, the light-attenuating effects of suspended sediment (i.e. "water clarity") can change somewhat independently of mass concentration and may in fact be a better measure of ecological significance than mass concentration *per se* (Smith & Davies-Colley, 2002; Davies-Colley et al., 2014; Hughes et al., 2015).

Water clarity has two main aspects that in practice are highly correlated: (1) 'visual clarity' that is, sighting range as it affects human recreational users, fish, marine mammals and aquatic birds; and (2) 'light penetration' as it affects, particularly, photosynthesis of both phytoplankton and benthic aquatic plants. These two aspects are different because the former is essentially a beam attenuation (i.e. decrease in intensity of a beam of light) and the latter is diffuse attenuation (where light scattered out of the beam can still contribute to diffuse light). In coastal zones, changes to light penetration can affect primary productivity, water temperature, and photo-degradation of organic matter (Julian et al., 2008) whereas changes to visual clarity can affect human activities, and animal behaviour. In coastal New Zealand, documented studies have shown that decreasing water clarity due to increasing sediment is eroding the resilience and role of photosynthetic communities like kelp forests or microphytobenthos thus threatening the delivery of ecosystem services by marine forests (like food production, cultural value, carbon storage) (Desmond et al., 2015; Tait, 2019; Blain et al., 2021). Reduced water clarity also exacerbates effects of increasing extreme marine heatwave events (Tait et al. 2021). Reduced visual clarity has been shown to be a significant constraint on river use for contact recreation (Davies-Colley & Ballantine, 2010). The adverse effects of reduced visual clarity in downstream estuaries include reduced feeding opportunities for visual predators such as some fish species and seabirds, while reduced light penetration may drive the decline of benthic plants such as seagrass.

Both visual clarity and light penetration are particularly affected by fine suspended sediment, whereas the concentration of coarse sediment tends to make up the majority of suspended sediment mass (and hence TSS concentrations) (Davies-Colley et al., 2014). In addition, fine sediment is a

[8] "Sedimentation" in this report means the deposition of sediment onto the seabed
[9] Australian and New Zealand Environment and Conservation Council

better tracer of pollutants than coarse sediments (Davies-Colley et al., 2014). In contrast, where fine sediment tends to stay in suspension, coarse sediment tends to settle to the seabed, where it can adversely affect ecosystem health by the process of infilling and shoaling, and smothering seabed biota (Thrush et al., 2004).

Practically, optical measures of TSS are easier to automate and measure *in situ* than gravimetric concentration. The former can be measured by optical instrumentation which enables continuous measurements at appropriate time and space scales whereas the latter requires water samples and laboratory analysis (Davies-Colley et al., 2014). Optical measures of suspended sediment are also easier and more accurate to measure by satellite remote-sensing methods.

However, even though suspended sediment is often the main driver of changes to water clarity in coastal New Zealand (Hughes et al., 2015), water constituents other than suspended sediment concentration also affect water clarity (Figure 2-1), especially coloured dissolved organic matter (CDOM, leached from decaying plant material in soils) and local growth of phytoplankton (autochthonous primary production). CDOM and phytoplankton can vary independently from suspended sediment concentration.

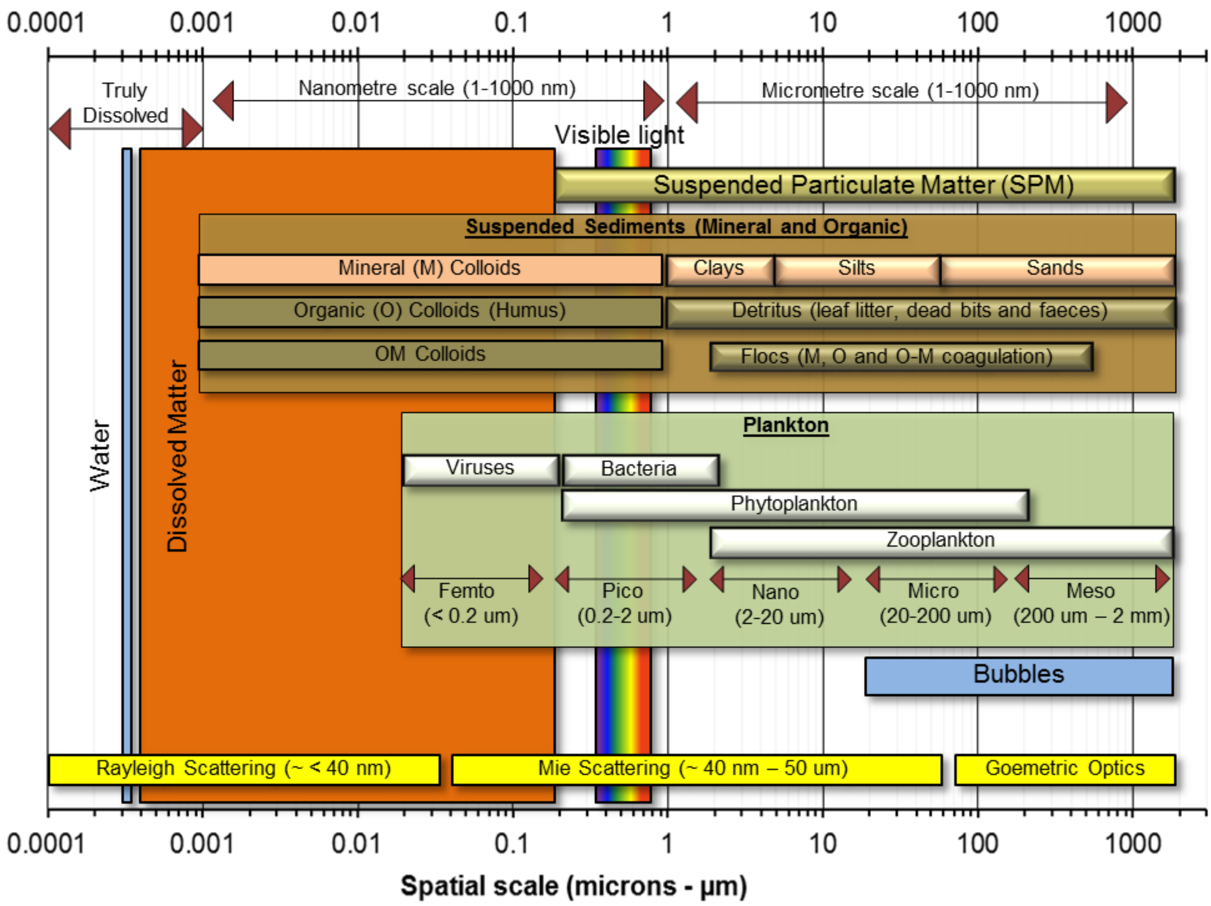

Figure 2-1: Optically significant components and their size perspectives to visible light wavelengths. The main scattering mechanisms are also shown. Although the division between dissolved matter and suspended particulate matter fractions is operationally divided by filtration at the 0.2 µm domain, contributions of the various groups is illustrated across this divide. Truly soluble compounds are typically < 1 nm.

2.2 Conceptual framework of coastal sediment flows

Elevated suspended sediment concentrations and CDOM are transported from catchments during flood events and dispersed in estuaries by buoyant river plumes. The greater the attenuation of light by suspended sediment and CDOM, the lower the water clarity.

Understanding and monitoring of the effects of sediment in the coastal zone can hence be separated into two parts:

A. **Sources of sediment**: How does suspended sediment get into the coastal zone?

- A1: Catchment to rivers: Where does the sediment come from (how does it get into the hydrologic system)? This combines rainfall (where, when, how much, how sudden, how prolonged), sediment-type (erodibility, grain-size/shape/chemistry), and removal pathways into a waterway.
- A2: Transport and deposition processes along the course of the river (including small streams). Vertical structure of suspended (mobile) sediment in the river
- A3: Coastal erosion: How much suspended sediment is introduced into the coastal environment by the local erosion of coastal land? This is affected by coastal geomorphology (the shape of the coastal landforms), the geology of the land (how erodible is it?), and the marine environment (wave/swell size/characteristics, water depth, tides).

B. **Redistribution and sinks**: What happens to suspended material when it reaches the coastal zone?

- B1: Estuarine reworking of suspended sediment arriving down the river (deposition, flocculation, biological response e.g. stimulated bacterial or phytoplankton productivity) - Figure 2-2. Vertical distribution of suspended sediment in the estuary/coastal zone, including estuarine density structure, vertical mixing (driven by wind, waves, tides).
- B2: Shelf-scale spatial redistribution: advective transport of sediment by waves, currents, tides and wind (e.g. Hunt & Jones, 2020). Vertical shear in currents. Mixing and formation of fronts. Movement of sediment offshore (out of the coastal zone e.g. into canyons). Fine sediment and dissolved riverine material entrained into coastal currents that advect more than 100km from their sources
- B3: Settling and resuspension: formation and movement of estuarine benthic boundary layers. It is important to examine whether the sediment deposited on the seabed is buried long-term or remains available to be periodically resuspended and this includes biological effects on resuspension of sediment e.g. bio-stabilization.

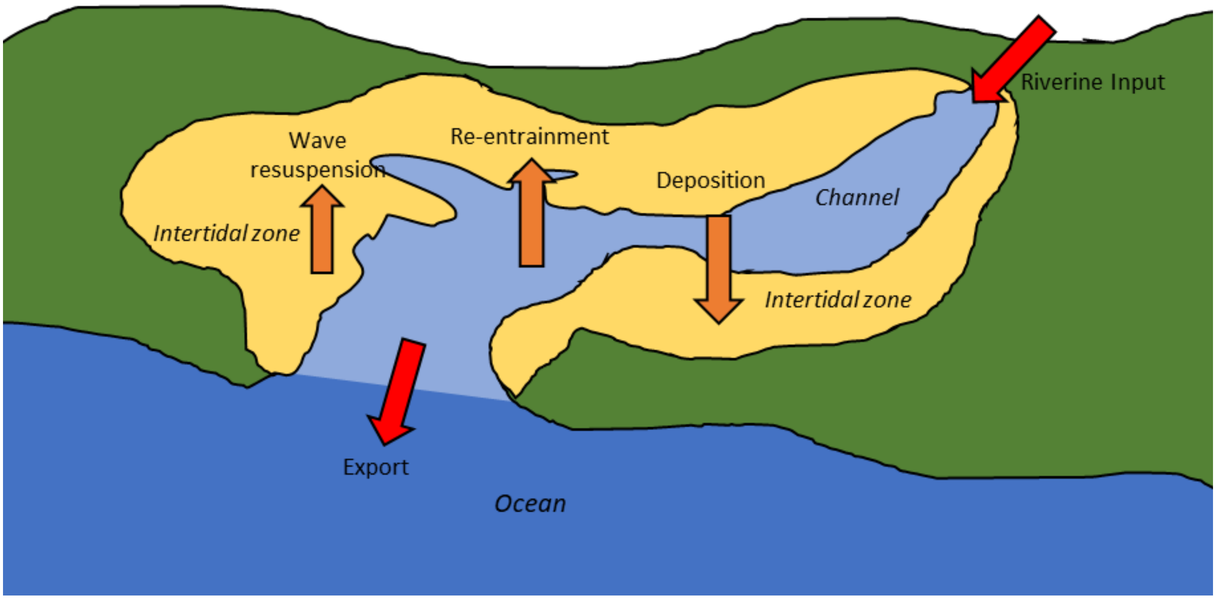

Figure 2-2: Conceptual diagram of an estuary showing the terms used in the sediment yield model. Sediment is supplied via riverine input and exported to the sea through the mouth. A fraction deposits within the estuary. Resuspension by waves occurs on intertidal areas, and re-entrainment by currents occurs in tidal channels. Source: Hicks et al. (2019) fig 2-2.

2.3 The role of satellite remote sensing in coastal sediment research

Satellite remote sensing gives us a direct observation of the combined optical effect all total suspended solids (TSS) in the coastal zone, irrespective of the type of particulate material, its source or behaviour. The satellite data just shows what suspended solids are present. Unpicking what exactly the satellite TSS product and its trends are telling us about sources or drivers of sediment, its behavior, ecological significance and the appropriate management response must be inferred based on other information. For example, observed trends in TSS could be due to modifications in land-use (e.g. deforestation, farming practices), climate change (e.g. phytoplankton production, rainfall patterns), or other factors (like wave climate, coastal development), or a combination of drivers. Hence, we recommend that satellite data is used to identify “hotspots” of change in TSS and water clarity to prioritise focused *in situ* and modelling studies. In terms of the conceptual framework above, satellite data is most useful for A3 (coastal erosion and resuspension), B1 (high-resolution satellite data can show TSS patterns in estuaries) and B2 (shelf-scale trends and redistribution of TSS). Satellite data in conjunction with models may also provide insights in B3 (settling and resuspension of sediment).

Satellite data is currently not useful for “sediment source” questions (A1 and A2 above). These questions are targeted by the “Catchments to Estuaries” research programme. This is a NIWA SSIF project led by Andrew Swales that aims to develop knowledge and tools to link diffuse-source contaminants (including fine sediments) generated by land use. Present research on suspended/fine sediment includes:

- River fine sediment dynamics – source and timing of suspended sediment load, and routing model
- Estuarine fine sediment dynamics – cohesive behaviour and transport.

- Fine sediment effects on benthic light climate and benthic primary production, including work on mapping methods and the effects of fine sediment on seagrass health (Nepheloid layer, light, substrate mud effects).
- Catchment to estuary fine sediment sources, transport and fate, including research on (1) compound-specific stable isotope analysis (CSSI) sediment-tracing methods (tracer behaviour, sources by land use & elevation, land to deep ocean); and (2) WETS (Wairoa Estuary -Tamaki Strait) model of fine sediment transport with multi-size fractions, cohesive, optical and deposition footprints.
- Estuary evolution model (decadal scale).

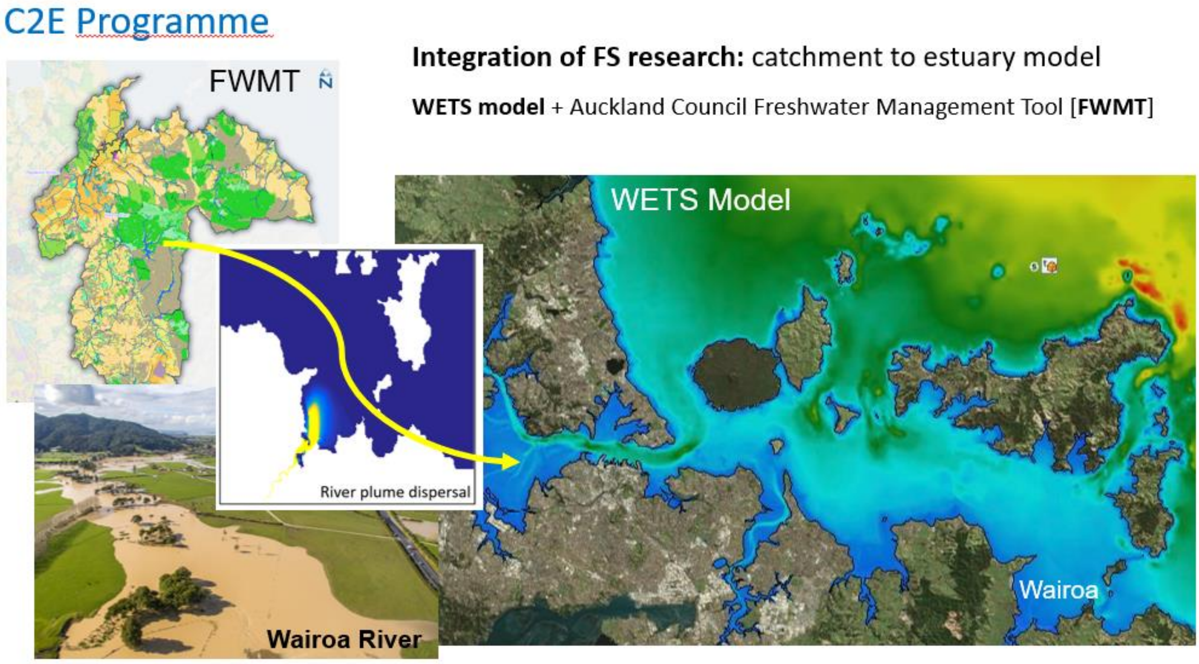

Figure 2-3: Schematic of part of the "Catchment to Estuaries" (C2E) research programme. Source: Andrew Swales, NIWA (2021)[10].

Satellite data can also potentially help to identify areas of the coastline where rivers (and sediment runoff in them) may be having the biggest effect can help to prioritise conservation efforts. As Fredston-Hermann et al. (2016) argue, integrated coastal management provides numerous methods to address land-based activities that generate coastal sediment, but many of these approaches are time-and resource-intensive. Often, conservation managers have few tools to aid in decisions about whether land-based threats that generate runoff are of sufficient concern to warrant further investment in planning and management interventions. To address this decision-making process, Fredston-Hermann et al. (2016) present a decision tree that uses geophysical and ecological characteristics to sort any marine coastal ecosystem into a category of high, moderate, low, or minimal risk from the land-based threats of nutrient and sediment runoff (Figure 2-4).

This method of classifying the areas where river runoff matters for coastal marine conservation could be applied to New Zealand using satellite data to identify the "impact radius" of rivers. Addition

[10] https://niwa.co.nz/freshwater/management-tools/sediment-tools/suspended-sediment-yield-estimator

required input information is available, including work on mapping the values of New Zealand's coastal waters (e.g. Beaumont et al., 2008, 2010).

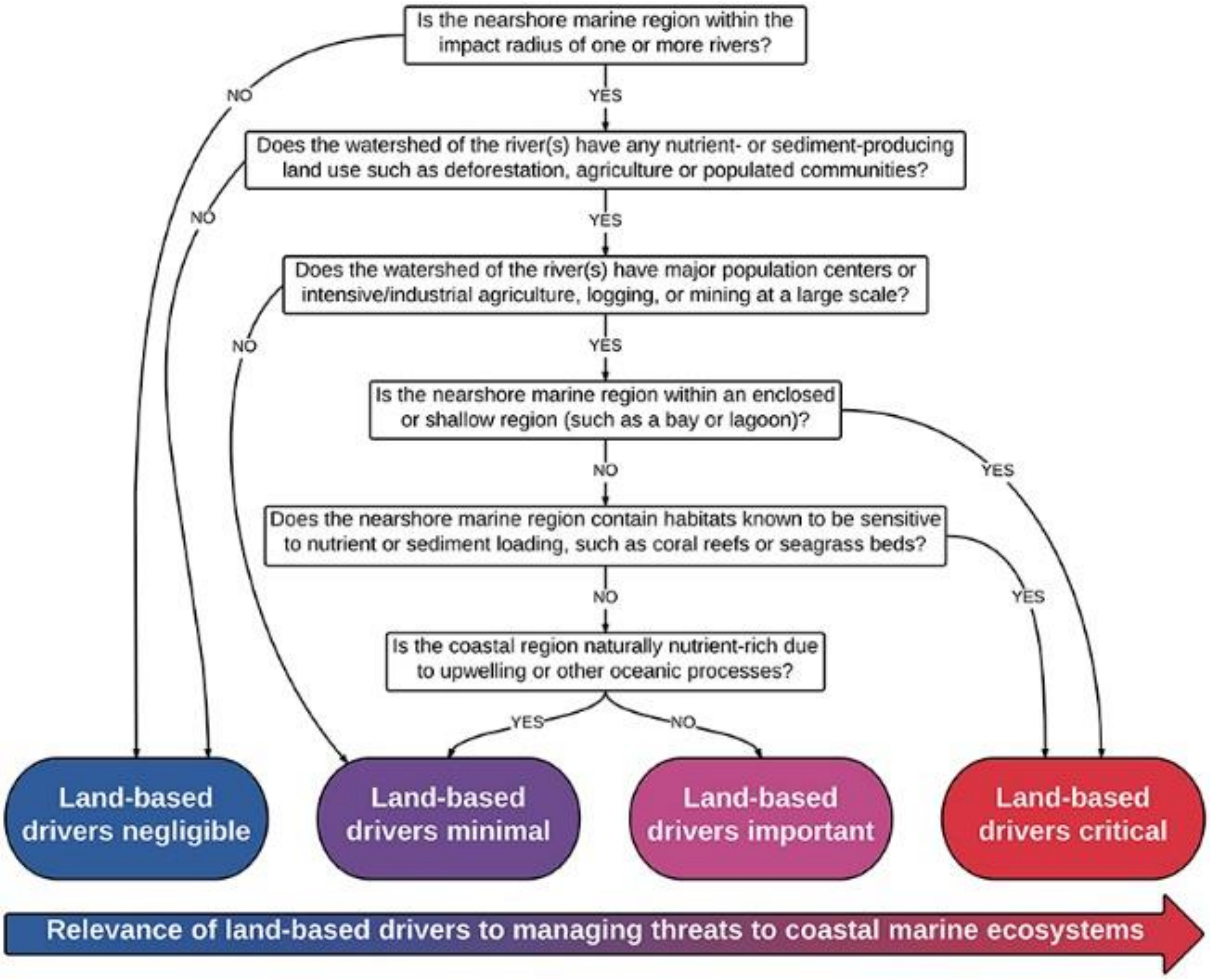

Figure 2-4: Relevance of land-based drivers to managing threats to coastal marine ecosystems. Source: Fredston-Hermann et al. (2016)[11]

[11] https://www.frontiersin.org/articles/10.3389/fmars.2016.00273/full

3 Satellite observations for coastal suspended sediment

3.1 Water colour and clarity

Material in the water gives it a distinctive colour and clarity. The "colour" is the spectral shape of the light leaving the surface of the water. This water-leaving radiance can be seen by a local observer looking down at the sea-surface. The light leaving the surface of the water also travels upwards through the atmosphere where it can be detected by a satellite sensor. The satellite remote sensing process takes this top-of-atmosphere spectral radiance and uses it to estimate the type and concentration of material in the water. In particular, suspended sediment gives water a distinctive brightness and colour that can be detected from space.

The optical properties of interest for modelling the colour and clarity of water are the absorption coefficient (a), the scattering coefficient (b) and the backscattering coefficient (b_b). Together, these three coefficients are called inherent optical properties (IOPs) (Kirk, 2011) as they are independent of the ambient light field.

Water scatters light equally in the backward and forward direction and absorbs red light strongly, giving it a blue-violet appearance when pure (Kirk, 2011). Coloured Dissolved Organic Matter (CDOM), introduced mainly from terrestrial sources in river plumes, imparts a yellow-brown colour to waters because of a strong trend of increasing absorption with declining wavelength, moving from red to blue through the visible spectrum (Bricaud et al. 1981). The shape, size and biogeochemical nature of particles also strongly influences IOPs. Pigmented particles (e.g. algae and bacteria photosynthetic pigments) absorb more light than non-pigmented particles (e.g. mineral grains), particularly red and blue light so as to leave water with a green colour. Smaller particles tend to scatter more than larger particles when expressed per gram, being more numerous with a greater cross-sectional area (Kirk, 2011), making water appear brighter in colour. While the bulk of light is scattered by particles in the forward direction, there are also biogeochemical differences in proportion of light backscattered (Stramski et al. 2004; Gallegos et al. 2008).

3.2 Space and time scales

The advent of satellite-based remote sensing has dramatically improved coastal monitoring (for harmful algal blooms (Schaeffer et al. 2015; Urquhart et al. 2017; Schaeffer et al. 2018a), primary production (Ye et al. 2015), aquaculture (Gernez et al. 2017; Snyder et al. 2017), surface water temperature (Schaeffer et al. 2018b), turbidity (Vanhellemont & Ruddick 2014) and oil spills (Hu et al. 2003). Many other uses have also been investigated (Valle et al. 2014; Tyler et al. 2016; McCarthy et al. 2017; IOCCG 2018; Schaeffer & Myer, 2019).

The utility of satellites for sediment studies depends on how well the satellite data capture the characteristic time and space scales of sediment in the coastal zone. Sedimentation and suspended sediment in the coastal environment is profoundly episodic, being influenced by transient events (flood events, river plumes, coastal erosion, and bottom resuspension) which typically occur on short space (from 10s – 100s of metres) and time scales (hours). The nature of this variability is crucial in the context of monitoring for change, and for understanding what satellite (remotely-sensed) observations can and cannot provide in the context of monitoring and improved understanding.

There are two main types of satellite sensors/datasets with different characteristics and different advantages and disadvantages (Table 3-1). In assessing the utility of satellite data for coastal sediment, it is important to distinguish between two types of satellite sensors (Figure 3-1): (1) those with moderate spatial-resolution (> 250-500 m) in the visible range, typically having narrow and more spectral bands for greater optical discrimination (designed for "ocean colour"); and (2) those with high spatial resolution (10-30 m) and wide spectral bands (optimized for "land colour". The contrast in spatial-resolution is clear in examples provided for Marlborough Sounds (Figure 3-2), and higher spatial-resolution is obviously desirable in near-shore, coastal environments. However, the price is that the quality of the estimates of TSS are poorer and the repeat-times longer for these higher spatial resolution sensors. These trade-offs are discussed more in the following sections.

Table 3-1: Summary of the two main types of visible-band satellite sensors/datasets available, showing their different characteristics and different advantages and disadvantages.

	Ocean-colour	True-colour
Spatial resolution	Moderate: hundreds of metres (250 m – 1 km; 500 m MODIS-Aqua) which precludes use in small estuaries and small inland waters	High: 60 metres (Landsat), now approaching ~1 m
Frequency of images of New Zealand	One or two images daily (MODIS). Monthly composites usually given complete coverage round New Zealand.	Image every 25 days historically, now every ~5 days (Sentinel-2). Only a few images of a given location each year
Period of existing data; consistency	1997-present (2002–present coastally); very consistent	1982–present (Landsat), Sentinel 2: 2015-present; different sensors not intercalibrated
Spectral resolution of sensors	7 or more narrow bands and extra for aerosol correction	3 broad bands (red-green-blue)
What the data provides	Water colour and clarity (attenuation); concentrations of water constituents. (including phytoplankton, total suspended solids, TSS) Quantitative accuracy of satellite products is variable and benefits from *in situ* sampling for satellite tuning and validation.	"Snapshot" pictures of water colour e.g. showing spatial patterns of sediment plumes. Estimates of TSS less accurate and less consistent over time.
Examples of sensors (recent historical and current)	SeaWiFS, MODIS, MERIS, VIIRS, Sentinel 3	Landsat, Sentinel 2, WorldView-2, GoogleEarth, ASTER

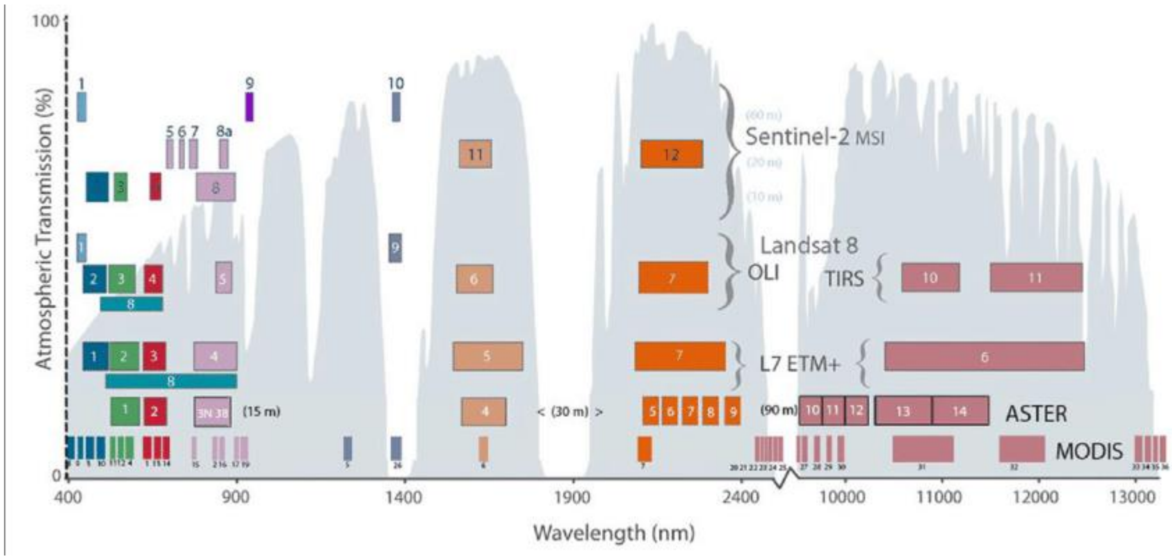

Figure 3-1: Comparison of spectral bands used in some common satellite sensors. The different colours show approximate colours of light in those wavelength bands. Note the narrow spectral bands of the moderate spatial-resolution satellites like MODIS (NASA), and the wide spectral bands of the high spatial-resolution sensors like Landsat (NOAA) and Sentinel-2 (ESA). Source: US Geological Survey.

Figure 3-2: Comparison of contrasting spatial resolution across Marlborough Sounds. Left: High resolution (Sentinel-2, 10-20 m); Right: Moderate-resolution (MODIS, 250-500 m). The bottom row is "zoomed in" on the white rectangle in the top row.

3.3 Moderate spatial-resolution satellites

3.3.1 Key characteristics

Several moderate spatial-resolution "ocean colour" satellite sensors have been operational over the last few decades. Crucially, these have *narrow spectral bands* which allow us to obtain an absolute estimate of the concentrations of coloured material in the water. These sensors have wide swaths[12], and cover New Zealand (and global) waters daily. This makes them useful for understanding patterns and change in suspended sediment around New Zealand. These sensors have the following key characteristics:

- multi-bands in the visible spectrum and near infra-red, with spectrally-narrow sensor bands (10–20 nm)
- moderate spatial resolution (250–500 m) adequate for coastal zones, large harbours/estuaries, and large inland water bodies
- sun-synchronous satellite orbits to maximise signal-to-noise ratios
- daily repeat for New Zealand

[12] A satellite "swath" is the width of the field of view of the sensor on the ground, i.e. how much of the earth's surface is seen on each satellite overpass.

- well characterised and calibrated before launch, and long-term reliability ensured by ongoing well-tracked radiometric calibration and validation (there is usually a whole team of people employed by space agencies to do this)
- processing integrated into "scientific community standard" satellite processing systems, e.g. SeaDAS[13].

3.3.2 Data processing

Data from moderate spatial resolution satellite sensors are either received locally (at the NIWA Lauder satellite receiving facility (Figure 3-3) or obtained by file transfer from NASA Goddard Space Flight Center (ocean colour) or NOAA (sea-surface temperature). At present, research at NIWA for mapping TSS in the coastal zone focusses on MERIS, MODIS-Aqua and VIIRS. However, Sentinel 3[14], which has 300 m spatial resolution, will likely also be used in the near future.

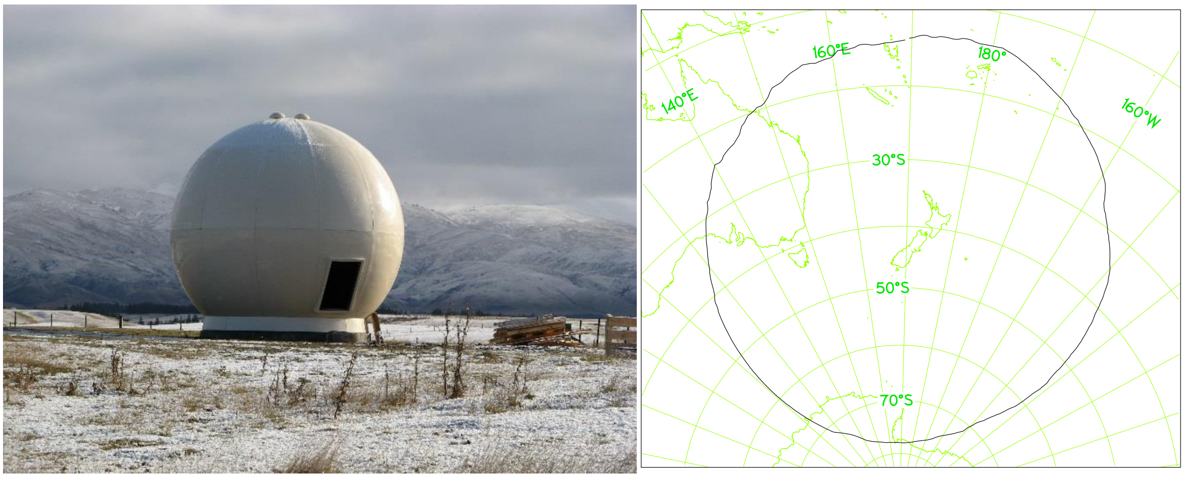

Figure 3-3: The NIWA satellite receiving station in Lauder. Left: the receiving station which downloads data from MODIS and VIIRS daily. Right: the area over which locally-downloaded data is received.

The data are stored and processed at NIWA in Wellington using the High Performance Computing Facility ("NeSI") and processed using methods described in Section 6.2.2. Note that we recommend using semi-analytical algorithms for processing ocean colour satellite data because this improves the robustness of estimates of water constituents. These semi-empirical algorithms relate ocean colour to the inherent optical properties (IOPs) of the water constituents rather than using purely empirical, local-regression approaches (e.g. Jiang & Knight, 2017). Although empirical components are still required, these relationships are more stable in space and time and robust to changes than band-ratio algorithms or their empirical adjustments.

Further developments in ocean colour algorithms, especially atmospheric correction over turbid waters, are likely to improve the quality, reliability and availability of data on TSS in the study region in the future. This means that periodic preprocessing changes the data, which has implications should the data be used for regulatory or legislative applications. For this reason, it is important that users:

[13] https://seadas.gsfc.nasa.gov/
[14] https://sentinel.esa.int/web/sentinel/missions/sentinel-3

- are aware of the magnitude of the uncertainties and limitations of the satellite data, so that the data are used appropriately
- maintain an explicit record of the version of satellite data used (for example, this is provided in NIWA-SCENZ)
- allow the possibility to revisit applications of the satellite data when newer (improved) products are available

More information on the approaches currently used to estimate TSS from moderate-resolution satellite data are given in Section 6.2.

3.4 High-spatial resolution satellites

3.4.1 Key characteristics

High spatial-resolution satellite sensors differ from those in Section 3.3 in that they typically have only a few, wide spectral bands (Figure 3-1). Broad spectral bands mean that estimates of TSS from these sensors are poorer than from narrow spectral-band sensors in Section 3.3. It is much more difficult to estimate concentrations of water constituents from broad spectral band data because there is less information contained in these data. Nevertheless, with sufficient care, for specific areas, these sensors are capable of mapping *relative* concentrations in TSS.

Several high-resolution (metres) radiometric (visible band) satellite sensors are available. These include Landsat (series of sensors including Landsat-5, -6, -7, -8 and -9 (joint NASA/USGS[15]) and Sentinel-2 (European Space Agency[16]).

The key high spatial-resolution data to use for sediment work in New Zealand are:

- Landsat 4-8 (1982 - present)[17],[18]: Spatial resolution 30 m and 16-day repeat.
- Sentinel 2 (2017 – present) [19]: Spatial resolution of 10-20 m and a 5-day repeat globally (2-3 mid latitudes). This is a good option for combining with and extending the Landsat series of data into the present era. As with Landsat surface reflectance, conversion to water reflectance is required to estimate water quality products and only prototype methods are available.

Other challenges with obtaining useful information on TSS from high spatial-resolution satellites include:

- Small coverage areas per overpass / long return periods (tens of days). These sensors typically image narrow swathes of the earth which means that repeat times (i.e. how often they produce an image of a given area) tend to be long. The repeat times of high spatial-resolution satellites are generally once every 10-25 days compared to once daily for moderate spatial-resolution sensors. As 6 out of every 7 images are cloudy (regionally dependant), only a few clear images of any given location are obtained per year. Some space agencies (e.g. European Space Agency) are launching constellations

[15] United States Geological Survey, https://www.usgs.gov/
[16] https://www.esa.int
[17] https://landsat.gsfc.nasa.gov/
[18] https://en.wikipedia.org/wiki/Landsat_program
[19] https://sentinel.esa.int/web/sentinel/missions/sentinel-2

of satellite sensors (e.g. Sentinel-2 sensors) to overcome this issue, but this brings with it different challenges in that all the sensors must be intercalibrated.

- Poorly-tracked long-term radiometric accuracy. The radiometric calibration of satellite sensors is often affected by launch, and then these sensors can lose up to 40% of their radiometric sensitivity over time because of degradation from cosmic rays. Methods exists to track these changes over time, but this is presently incapable of obtaining a radiometric calibration within the ±0.1% required for good retrieval of water constituent absolute concentrations. Maps of *relative* TSS concentration are much more robust to this radiometric uncertainty.

In return for these limitations compared to moderate spatial-resolution sensors, the spatial resolutions of these sensors can be very good (tens of metres or better) which makes than potentially very useful for lakes, rivers, small harbours and estuaries, sounds and fiords.

Also, for some applications, mapping of relative TSS concentrations (rather than absolute concentrations) may be sufficient. For example, relative patterns of TSS may be adequate for validating patterns of sediment transport in hydrographic models, investigating transport vectors of suspended sediment in the coastal zone, looking for “halo” effects around estuaries/development, or observing plumes from operations like dredging.

3.4.2 Data processing

The data volumes of the high-spatial resolution sensors are so very large that the trend is not to download these data locally but rather to interact with the data via cloud platforms. Google Earth Engine (GEE)[20] is a geospatial processing service powered by Google Cloud Platform. GEE provides an interactive platform for geospatial algorithm development at scale to enable high-impact, data-driven science. In this arrangement, the satellite data are held at central facilities overseas and accessed through cloud computing “on the fly”. The data resource has a comprehensive data catalogue, is well documented and resourced, with guides, reference material, technical support, and an active user community contributing open-access code. The size of the GEE data repository is currently several petabytes and growing.

GEE analysis and access is fast, reliable, and scalable (i.e. user-applications built on GEE do not suffer “bottlenecks” if many users access the application at once). A comprehensive review on GEE for remote sensing big data applications is provided by Amani, et al. (2020). Over 450 journal articles published in 150 journals between January 2010 and May 2020 were examined. Amani, et al. (2020) found that Landsat and Sentinel datasets were the most used by GEE users, and supervised machine learning algorithms, such as Random Forest, were widely applied to image classification tasks. The number of GEE publications have significantly increased during the past few years, and Amani, et al. (2020) concluded that expected the interface between GEE and “big data science” will accelerate in the next few years in all areas of remote sensing science.

GEE datasets (Landsat 4-8 and Sentinel 2) include surface reflectance over water, but most of the applications are terrestrial. Technical research effort is needed to estimate remote sensing reflectance from which water-processing algorithms can be applied. If this can be achieved, Landsat-Sentinel high resolution (30 m) datasets will be useful for suspended sediment management for the

[20] https://earthengine.google.com/

New Zealand CMA, as well as in freshwater bodies such as lakes, ponds, rivers and wetlands. Prototype methods for this exist (e.g. Pahlevan et al. 2021).

The following example (Figure 3-4) is based on "USGS Landsat 8 Level 2, Collection 2, Tier 1" data[21], and uses the red/green band ratio exponential empirical algorithm from (Pham et al. 2018) - being less sensitive to uncertainties in method for mapping suspended sediment compared to individual bands. Application of the Pham algorithm has not been verified for New Zealand waters. Ranges across coastal oceanic, estuarine and lake waters are believable for around Banks Peninsula and Te Waihora/Lake Ellesmere (Figure 3-4A) and Pelorus Sounds (Figure 3-4B). Extraction of timeseries for boxes in Pelorus Sounds, Kapiti Marine Reserve and Te Waihora/Lake Ellesmere (Figure 3-5), illustrates the poor repeat frequency of Landsat-8 data (because of 16 day imaging plus cloud cover). Additionally, differences between data from multiple images on the same day illustrates further quality control requirements. Analysis over the combined Landsat and Sentinel-2 time span (1982 – present) will improve temporal and spatial statistical power, providing a valuable analysis on regional differences and potential trends in suspended sediment, water colour and clarity changes.

[21] https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2

A

B

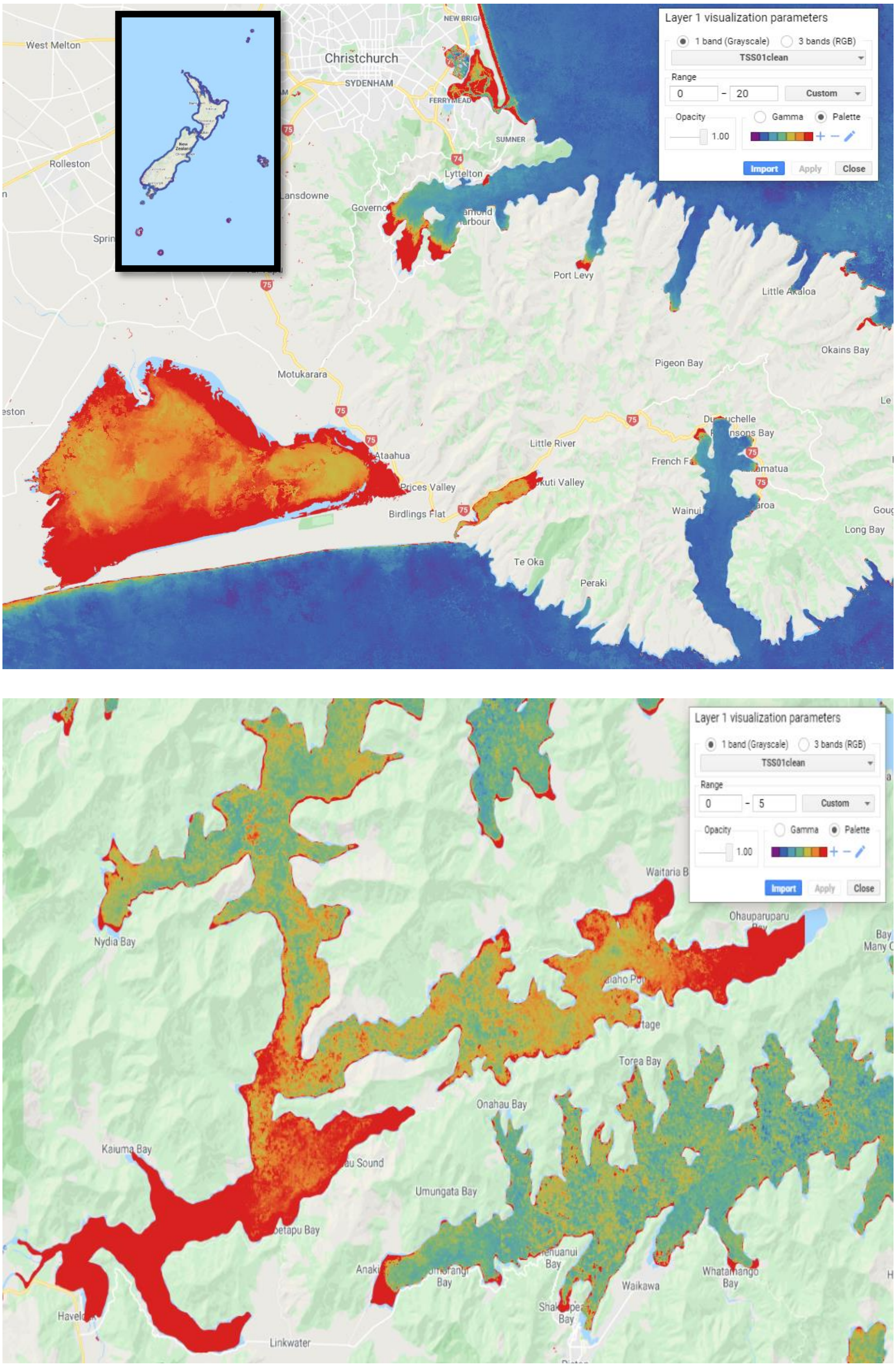

Figure 3-4: High spatial resolution (30 m) maps of total suspended solids (TSS) for our CMA (inset), focusing on two example regions. Annual median TSS concentrations for 2020 for (A) Banks Peninsula and Te Waihora/Lake Ellesmere (scale: 0-20 g m^{-3}) and (B) Pelorus and Queen Charlotte Sounds (scale: 0-5 g m^{-3}). [From Landsat 8 with data processed on a test application using Google Earth Engine].

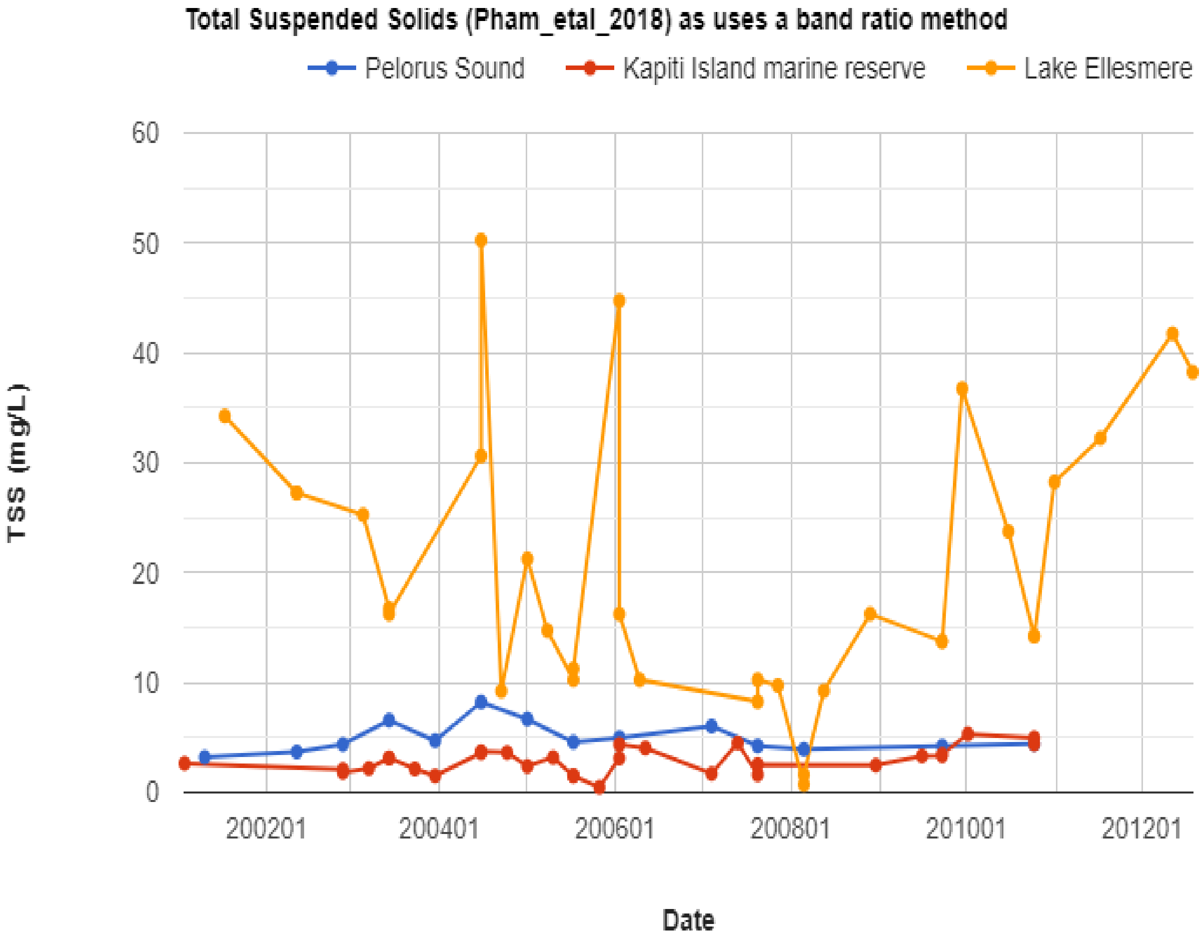

Figure 3-5: High spatial resolution (30 m) timeseries of total suspended solid concentration (TSS) at three locations around New Zealand. Extracted data for 2020 in areas within Pelorus Sound (near Havelock), Kapiti Marine Reserve, and Te Waihora/Lake Ellesmere. Note missing data due to cloud and duplicate data points on some days with high variation between values. [From Landsat 8 with processing on a test application using Google Earth Engine].

3.5 Scale-dependence

TSS concentrations in our CMA vary in space and time on a wide range of scales, meaning concentration is "scale dependent" (Onderka et al., 2012; Bracken et al., 2015; Vercruysse et al., 2020) – i.e. the "concentration of sediment" depends on whether the measurement method is small-scale (like taking a 1 litre water sample) or broad-scale (like a 500 x 500 m satellite pixel).

At a minimum therefore, the method used to measure the sediment concentration should be quoted when giving a value of the concentration. Also, this scale dependence means that care is needed when comparing measurements of sediment using methods with very different spatial scales. The same will be true for time-averaging. For example, Dorji & Fearns (2017) highlighted spatial-scale dependency by compared three different satellite estimates of TSS concentration in coastal waters of northern Western Australia: MODIS-Aqua (250 m), Landsat-8 Operational Land Image (OLI) (30 m), and WorldView-2 (WV2) (2 m). The high spatial resolution WV2 sensor reported a maximum TSS concentration 7 times higher than that estimated by the low spatial resolution MODIS-Aqua. When they were downgraded to a coarser spatial resolution of 5 km, differences of up to a factor of 3 were found.

Scale-dependency also has implications for comparing *in situ* and satellite-based methods of measuring sediment (see Section 3.7) and to compliance monitoring. For example, if operations (like dredging or discharge) are required to restrict TSS concentrations to below pre-defined limit, the method of measuring sediment must be given because point measurements of sediment (from analysis of water samples) will be more likely to exceed a given value than a large-area average from a satellite.

3.6 Limitations

Obtaining useful measurements of TSS from remote sensing methods is not simple nor are the data without issues.

- **Cloudy conditions:** The lack of satellite images in cloudy conditions may introduce a bias into the satellite data composites. TSS is likely to be positively related to the probability of cloud presence/absence. For example, TSS in the coastal zone are likely to be highest just after high rainfall events (elevated land-run off) and/or when high winds/high waves are present (higher coastal erosion and sediment resuspension). These situations are likely to occur when clouds prevent ocean colour satellites seeing the water surface. Hence, climatologies of TSS based on satellite data may underestimate actual long-term values. Field sampling can help to address potential bias in satellite observations (e.g. optically-instrumented moorings).
- **Near infra-red "glow" of land:** Near infra-red radiation can invalidate measurements within about 1 km of the shore. It is possible to extrapolate data from about 1-5 km offshore into the very nearshore zone by using statistical approaches. Although these methods can smooth small-scale (characteristic length scales of less than about 2 km) features in the very nearshore one, they are arguably preferred over lack of data for that monitoring time.
- **Satellite data processing failures:** The key processing components for satellite data are the atmospheric scheme (e.g. Wang & Shi, 2007) and the in-water semi-analytical algorithm (e.g. QAA, Lee et al., 2014). Both of these parts of the processing can fail for a variety of reasons including low solar elevation, poorly characterized optical properties of aerosols, cloud-edge effects, or unusual water constituents. The combination of cloud cover and satellite processing fail (including from land glow) is shown in Figure 3-6. TSS data are available for about 15% of the time (about 1 days per week on average), but this varies regionally and seasonally.
- **Surface water estimates:** Satellite observations are sensitive only to material near the water surface (to about 1 optical depth or about one-fifth of the euphotic zone depth). This can be a few cm in turbid coastal waters or tens of metres in clear ocean water. This means that satellites provide no information on subsurface structures or deep layers (stratification). This is a particular issue in two cases: (1) estuaries where strong vertical stratification occurs because of the presence of distinct salinity layers (e.g. salt-wedge estuaries); (2) areas where the concentrations of sediment are so high that most of the transport of sediment is in the dense hyperbenthic boundary layer rather than being more evenly distributed over the water column.
- **Shallow and clear water:** If the water is shallow and clear, the seabed can affect water-leaving radiances and render estimates of water constituents are invalid. A test

can be made comparing water depth and the optical attenuation length (from the satellite data) to suggest whether this is an issue, but because of geolocation issue, this will not be foolproof.

- **Accuracy:** The accuracy of satellite algorithms (which estimate concentrations of material in the water from spectra of ocean colour) can vary regionally. The process of characterizing the inherent optical properties of water constituents regionally around the New Zealand coast is ongoing but is rendered more complex by variability in the optical properties of sediment over time. For example, the type of sediment brought into the coastal zone in rivers is of a different type if there is heavy rainfall immediately after a period of dry weather compared to if the rainfall is sustained. There may also be seasonal variation in the optical properties of sediment from rivers.
- **Historical length of timeseries:** Consistent satellite observation start in 2002, and so earlier changes to water quality have not been observed, especially those during the period of deforestation of New Zealand (Julian et al., 2017; Hicks et al. 2019). Thrush et al. (2004) notes the risk of “sliding baselines” with regard to coastal sediment and sedimentation, where in many cases sediment loading increased early on in the history of human exploitation of the landscape with little knowledge of early “pristine states” (Dayton et al. 1998).

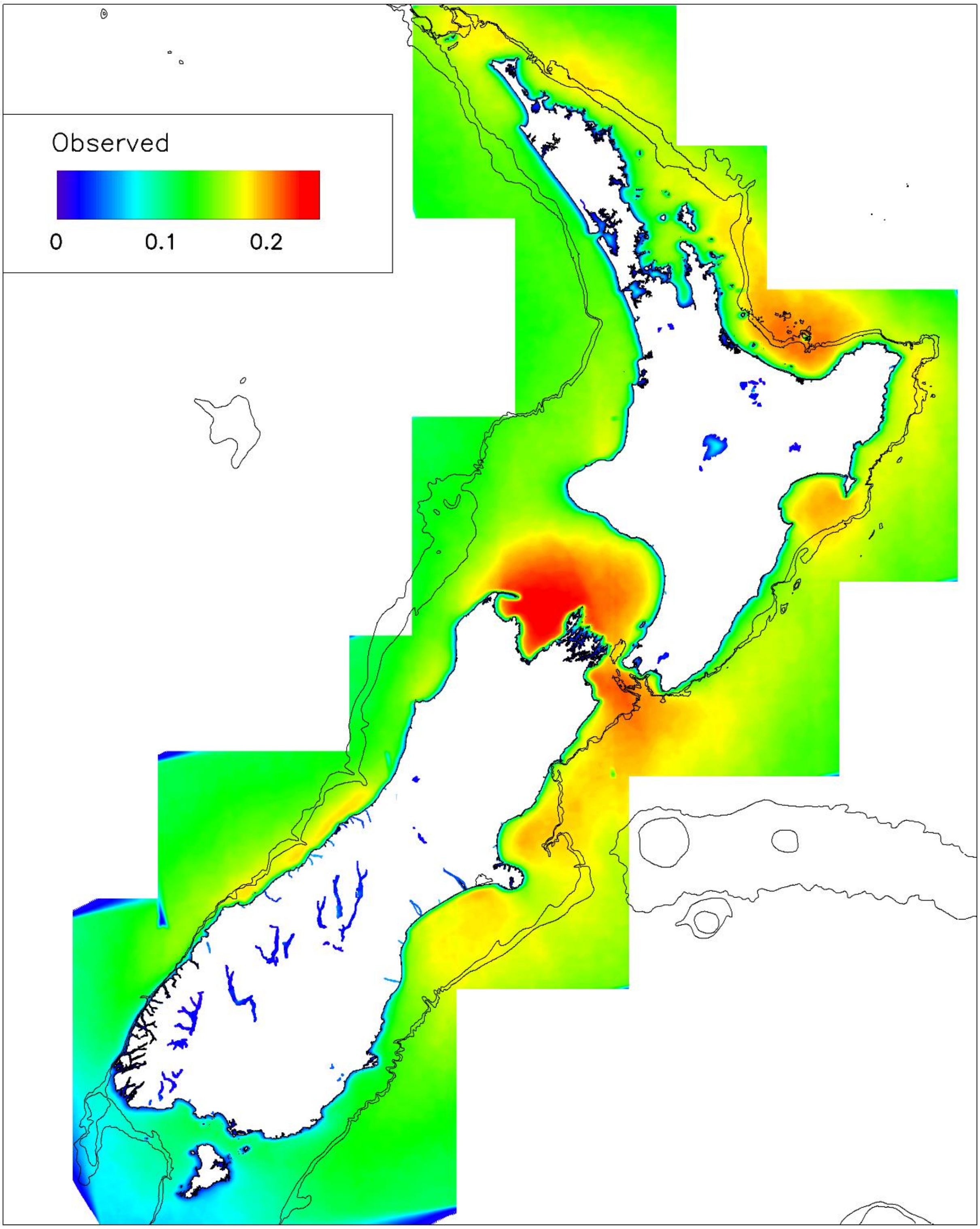

Figure 3-6: Proportion of satellite measurements that leads to a valid estimates of TSS concentration. The combination of cloud cover (which stops the satellite seeing the water) and failure of the processing methods for satellite observations (see text) leads to TSS data only being available for about 15% of the time (1 day per week on average). This data includes the use of an inshore extrapolation method.

3.7 Sampling in support of satellite methods

Developing locally tuned algorithms, and assessing the accuracy of ocean colour data using paired measurements of *in situ* water collections and satellite products is challenging for several reasons:

- A large amount of sampling is needed to build up sufficient data for statistically robust analysis and the majority of the New Zealand coastal zone is obscured by cloud on most days (Figure 3-6). It appears that cloud-cover has slightly reduced in the last 20 years in the CMA but the trend is small. Conditions in the coastal zone can be highly variable over short periods so that sampling close to the time of the satellite overpass is desirable; otherwise, conditions may change substantially between sampling and satellite measurement. This is especially true in regions with high influence of the tide or river flow (e.g. estuaries) and across sharp gradients (e.g. river plumes) where changes over short periods can substantially affect the optical properties at a given point. In a study with Environment Canterbury using *in situ* dataset of 721 measurements, we found that there were only 20 matchups with satellite data on the same day, and even these were usually separated in time by several hours.

- Scale-dependency (Section 3.5) leads to inherent (fundamental) differences between satellite and *in situ* measurements at the same location: ocean colour satellites measure the average radiometric signal over a large area (at a minimum 250 m by 250 m) whereas field sampling collects about a liter of water. Small scale variability will hence affect comparisons between *in situ* measurements and satellite observations of the same place at the same time ("end-to-end match-up"). Note also that the geolocation accuracy of satellite data like that from MODIS-Aqua is approximately ±500 m, and this can also introduce errors when matching-up satellite data and *in situ* measurements in enclosed water bodies with strong spatial gradients and temporal variability in water quality.

- There are two separate kinds of processing needed to estimate TSS from ocean colour measurements, atmospheric correction, and in-water inversion. End-to-end comparisons cannot distinguish errors arising from these two parts of the processing. This means that the robustness of processing method to variations in the combination of atmospheric and biogeo-optical properties cannot be investigated.

However, despite these challenges, long-term water collections at fixed locations can still be useful for understanding: (1) the range of suspended sediment concentrations and (2) their characteristics (type, particle size distribution, inorganic and organic content, stratification). *In situ* sampling should take into account management priorities and coastal importance: is sediment an issue for this location? This assessment can be informed by whether the satellite data suggest that suspended sediment concentrations (or other characteristics like water clarity or phytoplankton abundance) are changing at that location and if the ecosystem is likely to be sensitive to sediment. For helping improve the satellite data quality, it would be useful to target *in situ* measurement in locations with low levels of coastal natural variability over time, which are far enough offshore (>1 km) to get good satellite data quality, and which span a range of natural conditions (e.g. from low to high sediment concentrations; muddy sediment to refractory sediment). Coupling *in situ* sampling with *in situ* equipment (such as moorings or buoys: See Section 4) is recommended to enhance useability, particularly if consideration is given a site to which satellite sensors have high observation frequencies.

Hence, to improve and validate the quality of satellite data, we recommend that two kinds of sampling be carried out: (1) long-term, time-series sampling of key parameters in selected locations (which could be carried out by a variety of organisations) in conjunction with fixed instrumentation; and (2) more detailed vessel-based bio-optical surveys carried out as part of a research project using specialized sensors/techniques for bio-optical characterisation.

3.8 Data access and exploring satellite data for New Zealand (NIWA-SCENZ)

Although substantial satellite data exists in the New Zealand coastal zone, accessing this has traditionally been difficult for several reasons, including:

- the data volume is high (hundreds or thousands of files, data volumes of a few Tb[22]);
- the data have complex file formats (typically georeferenced binary netCDF format[23]);
- the data from other providers (e.g. NASA, EOS etc) are of low spatial resolution (4-9 km).
- the data from other providers use open ocean algorithms (‘Case 1’), which are not suitable for optically complex coastal waters (‘Case 2’).

Consequently, using multiple funding sources (NIWA SSIF, Envirolink Funding), a web-based portal was developed (2018-2020) to help users access of satellite (MODIS-Aqua) water quality products. The system is called NIWA-SCENZ (Seas, Coasts, Estuaries New Zealand) and the data provided are at moderate spatial (500 m^2) resolution, covering the period 2002-present and include 10 products. NIWA-SCENZ provides Regional Councils and Local Authorities, along with other research scientists and stakeholders, access to more than 19 years of satellite observations around the New Zealand CMA. A summary of data and capability in NIWA-SCENZ is given in Appendix A.

NIWA-SCENZ datasets extend from the coast out past the 12 nm mile limit and continental shelf boundary. GIS compliant maps (NZTM) are managed in an image service layer (data-cube) on an ArcGIS server (ArcGIS Enterprise - ESRI). Image services include timeseries, climatologies and anomalies, for median timesteps (weeks, months, seasons, and years) from mid-2002. Image services have been optimised for efficient data display and extraction of an area and timestep of interest. Extracted data are saved locally as csv files for further analysis (e.g. Shiny-SCENZ (Monthly) - R). Shiny-SCENZ is a collection of interactive graphics and analyses of relevance to interpreting monthly space-time water quality data and includes an overview map, summary statistics, timeseries plots, normalised timeseries plots, month trends, seasonal trends by LOESS (STL) with forecasting, spatial mapping, and Hovmöller diagrams (transect spatial changes through time). Current products include: Absorbance of particulate and dissolved detrital material; Backscatter of particulates at 555 nm; Chlorophyll *a*; Light at seabed; Horizontal visibility distance; Light attenuation coefficient of PAR; Proportion of observations; Secchi disk depth; Sea surface temperature; and Total suspended solids. Updates of timesteps is automated (weekly), while major reprocessing and new products will occur manually as needed. Notwithstanding the challenges and limitations given in Section 3.6, we expect NIWA-SCENZ to provide a valuable resource for New Zealand water quality environmental monitoring standards across sea, coast, and estuarine boundaries.

The key applications of NIWA-SCENZ:

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[22] Terrabytes
[23] https://www.unidata.ucar.edu/software/netcdf/

- Viewing true-colour daily images at full resolution (as fine as 250 m);
- Looking at satellite estimates of various water quality “products” for a given time.
- Looking at the typical seasonal patterns in water quality conditions (e.g. is TSS higher in winter than summer?)
- Exploring to what extent the water-quality conditions at a given time are unusual compared to normal conditions over the last 20 years.
- Extracting and analysing satellite data for a user-defined region. There are then a lot of statistical and visualisation analysis tools in shiny-SCENZ to explore these data, for example, to do trend analysis.

4 *In situ* and aerial observation of coastal sediment

As well as collecting water samples for analysis, it is possible to measure sediment and water clarity using *in situ* instrumentation. There are two approaches: (1) radiometric (i.e. by measuring the *colour* of the water and using this to infer sediment concentration and water clarity); and (2) transparency (i.e. by measuring the clarity of the water directly from a sensor immersed in it). The former approach uses some kind of camera or imaging system that looks down at the surface of the water, whereas the latter is immersed in the water and typically measures the way that a light beam interacts with material in the water. An effective approach to measuring sediment requires determining the sensors to use, and their method of deployment.

4.1 Radiometric observations

4.1.1 Types of radiometric sensors

In this context, radiometric sensors are "cameras" that measure the colour of light across field of view, and hence produce a coloured image. Data from this image can then be geo-rectified (i.e. mapped onto a known map or projection) and used to estimate water quality parameters such as sediment concentration.

As with satellite sensors, there are two types of radiometric sensors: (1) narrow spectral-band and (2) broad spectral-band sensors. Broad spectral-band sensors include low-cost cameras like GoPros, which have three bands (red, green, blue: RGB), sufficient for reproducing (approximately) what the human-eye sees. Narrow spectral-band cameras have more spectral bands, and include multi-spectral sensors with typically 5-15 bands, and hyperspectral cameras with hundreds of bands.

To estimate concentrations of TSS quantitatively from an image requires narrow-band sensors rather than the wide spectral-band sensors which are appropriate and widely-used for terrestrial mapping. In terms of cost, multi-spectral and hyperspectral cameras are much more expensive than RGB cameras; a hyperspectral camera costs ~$100k compared to a ~$10k for a good RGB cameras (ten times as much), and the data are more challenging to use and process. Multi-spectral sensors must also be well-calibrated (to an absolute radiometric standard), which is in itself technically challenging.

4.1.2 Aircraft and helicopter surveys

Many agencies carry out aerial surveys using cameras on small aircraft, and others have sampled coastal water quality using equipment lowered from helicopters. A number of commercial agencies offer aerial (mainly aircraft) surveying and mapping services[24,25] However, these services almost exclusively focus on terrestrial or shallow-water benthic surveys, and the capacity to map water quality (and sediment) is not generally offered.

4.1.3 Drone surveys

Although drone capability is also widely available commercially[26,27], these services are focused on RGB-applications over land. To use drones to map suspended sediment in the coastal zone faces the following issues:

[24] https://www.aerialsurveys.co.nz/
[25] https://landpro.co.nz/what-we-do/aerial-survey-and-mapping/
[26] https://www.ferntechcommercial.co.nz/surveying
[27] https://www.recon.nz/recon-services/aerial-mapping

- Multi-spectral or hyper-spectral sensors are required to be flown (rather than RGB-sensors) and these sensors are larger, heavier, more expensive, and produce greater data volumes.
- Flying drones over water is more risky than over land because a safe emergency landing is not usually possible, so any technical malfunctions are likely to lose the drone and instrument. Nesting seabirds often display aggression towards drones and could this could lead to "bird-strike" or disturb the animals.
- The area of coverage of a drone is typically much less than for an aerial survey from a small plane or helicopter because of maintaining line-of-sight between drone and operator. Also, drones are not allowed to fly in some areas (e.g. near airports).
- Weather conditions (especially moderate-high winds) can halt drone operations.

However, recent developments (see Case study below) have progressed the development of drone-mounted observations applicable for sediment mapping in the New Zealand coastal zone.

Case study: Low-cost narrow-band radiometric sensors. In a NIWA-led project in 2018-19, developed a prototype small, low-cost, aerial camera system for measuring water quality (including TSS) and mapping coastal habitats (Pinkerton et al., 2019; Figure 4-1). The project was funded by Royal Society New Zealand (Catalyst Fund) and included colleagues from the University of Oldenburg (Germany) and New Zealand drone-specialists, X-Craft Ltd (Auckland). The project made substantial progress on testing a camera system that could be flown on drones (both multicopter and fixed-wing) but more development work remains to be done. The project found that a low-cost sensor (<$10k) with 4 narrow bands is likely to be adequate for measuring water quality (backscatter, suspended sediment, phytoplankton) provided that light reflected from the water surface can be avoided or corrected for within 5% which is feasible. The system was trialled a variety of sensors combinations in regions including Wellington Harbour, Lake Wainamu, Kaikoura, Hauraki Gulf, and Goat Island to validate the model results.

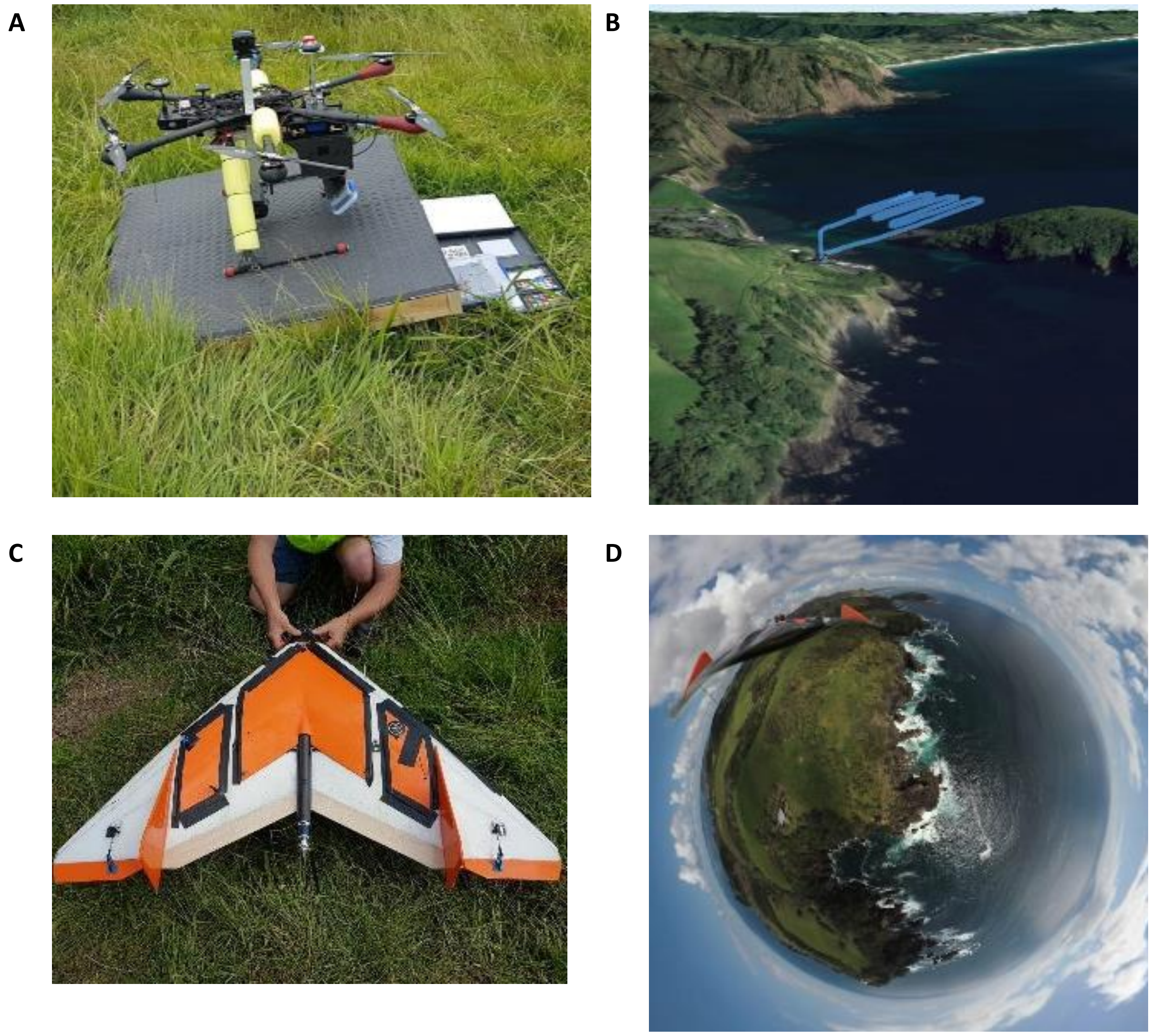

Figure 4-1: Testing radiometric measurements from drone at Leigh Marine Reserve, Cape Rodney. (A) Hexacopter drone (X-Craft) showing central top and bottom Garmin Virb 360 cameras and black active gimbal (with GoPro Hero 4, Micasense RedEdge, and Ocean Optics hyperspectral radiance sensors) pointing at 40 degrees from nadir. Calibration plates are in front of sensors to bracket pre-flight and post flight data. (B) One coastal habitat mapping survey track in Google Earth between Goat Island and Leigh Marine Reserve. (C) Valkyrie fixed wing drone (X-Craft) with Garmin Virb 360 inserted into nose. (D) One image example from Valkyrie drone video footage.

4.1.4 Shore-based cameras

It has long been recognised that water-viewing cameras at fixed shore stations can provide a plethora of information potentially relevant to coastal management. For example, the “Cam-Era” project[28] at NIWA is a network of computer-controlled cameras that monitor the New Zealand environment for research and resource management. Cameras have been operated long-term from sites including New Brighton Pier, Pauanui, Raglan, and Tairua. The main applications to date have been to investigate beach profile (and changes over time), and wave and surf characteristics. This method is likely to be a cost-effective and low-tech way of gathering information on the spatial patterns of sediment over long-periods at high frequency (every few minutes during daylight hours)

[28] https://niwa.co.nz/our-services/online-services/cam-era

provided that: (1) the obliqueness of the view is not too great, or if the camera can be relocated (or a new camera added) with a less-oblique view of the water; and (2) the patterns of sediment in the water are relatively pronounced (e.g. distinct plumes of suspended sediment are present). Limitations are that:

- Sometimes finding a suitable high vantage point for the camera will not be possible
- The cameras have broad spectral bands and so only relative concentrations of TSS will be obtained. This means the data will be suitable for estimating only the relative spatial patterns of TSS, rather than absolute concentrations, and tracking change over time could be relative only. Well-designed *in situ* sampling could provide local tuning of the processing algorithms to overcome this challenge.

Case study: In collaboration with GroundTruth Ltd, a Garmin Virb 360° camera was installed on an existing Kapiti Island telemetry station (Figure 4-2). The site overlooks coastal waters and has captured, at 10-minute intervals, sky and coastal sea-state conditions, since instalment on the 18 November 2018 (Figure 4-2). This timeseries is expected to continue, providing a comprehensive timeseries across day, week, month, season and annual scales.

Figure 4-2: Kapiti Island fixed station telemetry site. A Garmin Virb 360° camera was integrated into the existing telemetry site at northern end of Kapiti Island overlooking the marine reserve (left) giving images (example right).

4.1.5 Vessel-based cameras

Radiometric imaging sensors like RGB[29] cameras or multi-/hyper-spectral cameras can be installed on vessels to obtain information on the colour of the water, from which, estimates of TSS concentrations and distributions can be obtained. For example, Yachts in the Volvo Ocean Race are all equipped with lightweight instruments to measure the colour (and temperature) of the water. A black box acts as an onboard computer, gathering the results from the sensors, which are also embedded in the keel. Once the black box has collected the data it puts it into a format that can be beamed back via satellite using the yachts' navigational transmission systems. The data is sent to the project's headquarters at the Southampton Oceanography Centre (UK) where it is used to estimate phytoplankton concentration. Similar sensors could be used to estimate TSS in coastal zones.

As another example of this approach in New Zealand, with NIWA SSIF funding, a Garmin Virb 360° camera was installed permanently on the NIWA research vessel *RV Tangaroa* on 22 November 2018. Mounted on the central forward mast of the monkey island, it provides total sky and sea state conditions at 5-minute intervals surrounding the vessel. It was installed in this position to capture

[29] Red-green-blue, RGB

coincident data with recently installed TriOS RAMSES (Germany) hyperspectral sky and sea surface water leaving radiance (colour) sensors. Together, over time, the radiometric sensor and sky camera will provide data that can be used to improve the quality of satellite observations of water quality in New Zealand in a cost-effective way.

4.2 Immersed instrumentation

4.2.1 Types of immersed optical instrumentation

Some of the more common types of immersed optical sensors are shown in Table 4-1. These instruments typically measure some aspect of the clarity of the water: the interactions of a light beam with particles or dissolved material in the water. As such, they are all affected by coloured material that co-occurs with sediment (such as phytoplankton, or CDOM[30]) and they are all sensitive to differences in the type of suspended particulate material. The key characteristics of sediment are the particle size distribution, minerology of the sediment (particle size, refractive index, density), and whether the particles are coated in organic matter (which affects their absorption properties).

[30] Coloured Dissolved Organic Matter

Table 4-1: Immersed bio-geo-optical instrumentation relevant to sediment. All immersed optical instrumentation is subject to biofouling and sensitivity (calibration) drift. Several anti-fouling measures exist and are widely used, including copper-based shutters, brushes, and pumped chemical antifoulant. Immersed sensors must be removed, recalibrated, and replaced approximately once every 3 months (depending on conditions at the deployment site, sensor type, and the effectiveness of antifouling methods).

Sensor	Description	Advantages	Disadvantages
Optical backscatter, including turbidity (broad optical backscatter)	Measure the amount of light scattered by particles in the water.	Wide range (so can cover clear water to highly turbid conditions). Relatively cheap. Widely used. Multispectral optical backscatter sensors are available.	Turbidity sensors from manufacturers vary, especially: (1) different colours (red, green, blue, white) of light; (2) different angles of scattering measured. See also: Downing, (2006); Davies-Colley et al. (2021)
Beam transmittance (attenuation)	Measures the attenuation of light by material in the water	Moderate range. Medium price. Moderately easy to use and with wide use. Recommended as proxy for fine sediment (Davies-Colley et al., 2014).	Affected by all material in the water so separating the effects of absorbing material (CDOM) with scattering material difficult. Transmissometers for sediment typically use red wavelengths to reduce this effect.
Absorption-attenuation (AC)	Has two tubes which measure attenuation and absorption simultaneously.	Widely used (for research). Characterises key inherent optical properties. Multispectral and hyperspectral options	Expensive, and somewhat difficult to calibrate and operate. More a research-tool than an operational (monitoring) tool.
VSF (Volume Scattering Function)	Measures backscatter at 3 wavelengths and 3 angles	Characterises spectral shape of backscattering which is a key parameter in coastal satellite algorithms	Expensive, and somewhat difficult to calibrate and operate. More a research-tool than an operational (monitoring) tool.
ECO-triplet	Range of sensors including: chlorophyll, CDOM, backscatter	Small, compact, medium-price. Widely-used. Range of sensors to choose from. Built-in anti-antifouling.	Requires regular calibration
Radiometric	Radiometric sensors for measuring intensity of light reaching the seabed	Small, compact, long-duration	Subject to biofouling during extended deployments

Although these are probably the most commonly-used approaches for investigating sediment concentrations, bio-optical properties and the underwater light field, a variety of other methods are available or under development (e.g. Rai & Kumar, 2015; Pearson et al., 2021). New methods based on optics, acoustics, density, and conductivity have shown promising results in the direction of continuously measuring suspended sediment concentration. Already technologies based on turbidity (back- or side-scatter), laser diffraction, acoustic backscatter, are widely applied in field conditions, whereas others are under development. Measurement stability, range, and tractable calibration remains an important aspect associated with these technologies.

As noted in Table 4-1, turbidity sensors from different manufacturers and of different designs vary, especially: (1) different colours (red, green, blue, white) of light; (2) different angles of scattering measured. To improve comparability of turbidity measurements, manufacturers typically design sensors to a particular standard (e.g., ISO-7027; ISO, 2016) and standard methods for turbidity measurements and calibration have been developed (e.g., NEMS[31]). Despite these efforts, residual variability in instrument design and the lack of a strict physical definition of “turbidity” makes turbidity *per se* unsuitable as a standard measure of water quality (Davies-Colley & Smith, 2001; Bright et al., 2020; Davies-Colley et al., 2021). However, several New Zealand studies (Section 5) show that turbidity (ideally measured across a range of water types by a single instrument) can be useful as a proxy for optical backscatter as measured by satellite sensors. In particular, when measured with TSS, estimates of optical backscatter can help bridge the gap between satellite and *in situ* measurements without the need for end-to-end (i.e., satellite versus *in situ*) matchup comparisons.

Multi-spectral backscatter sensors can measure the spectral shape of backscattering, a factor which varies depending on the relative amount of phytoplankton and non-algal particles present (and their type) and which affects the accuracy of satellite estimates of chl-a. It is expected that improving knowledge of this factor will help us to partition backscatter by algal and non-algal particles in the future and so improve the utility of satellite data for understanding coastal sediment.

4.2.2 Moorings (instrumented buoys)

Timeseries data from coastal buoys is a tool to provide accurate medium to long term variability of suspended sediments at a single location. Coastal buoys provide high-resolution timeseries data and operate in two main modes: 1) delayed mode or 2) real-time observations. Data from coastal buoys can be obtained from either the surface, subsurface or both depending on the observing priorities for a particular location. To resolve suspended sediment signals originating from rivers, near-surface observations are required, which is typically shallower than the upper 5m of the water column.

Coastal moorings in delayed mode typically have no surface buoy and have a subsurface string of instruments that internally record data. Coastal moorings require regular maintenance trips to retrieve data, replace batteries and clean biofouling on instrumentation. This type of maintenance work is done by a skilled team from coastal vessels. Real-time coastal buoys benefit from solar panels for powering instruments and data collection. Regular cleaning of buoys and instruments is still required to maintain data quality. Best practices for coastal buoy data includes regular instrument calibrations and is done in conjunction with an *in situ* water sampling programme for localised range calibrations for turbidity and/or suspended sediment concentrations.

4.2.3 Seabed light sensors

Changes to the amount of light reaching the seabed can have profound effects on benthic and demersal communities, especially where seagrass, macroalgae or microphytobenthos are present (Desmond et al., 2015; Tait, 2019; Blain et al., 2021). Small, self-contained radiometric sensors (e.g. HOBO sensors[32]) are increasingly used to track changes in the amount of light at the seabed to investigate the effect of changes in water clarity on these communities.

Despite being relatively cheap, HOBO sensors require frequent calibration (lumens to PAR using LiCOR; Long et al. 2012) and cleaning due to biofouling to ensure data quality and continuity. Given

[31] https://www.lawa.org.nz/media/3198184/nems-turbidity-final-draft-version-as-at-29-aug_sent-fior-lawa-prior-to-workshop-.pdf
[32] https://www.hobodataloggers.com.au/hobo-pendant-ua-002-64-temperaturelight-data-logger-64k

their measurement of seabed light, these sensors require skilled underwater scuba teams for deployment and recovery. Such light sensors have been used in ecological studies around New Zealand to determine the role of seabed light in shaping ecosystems and the negative role of coastal sedimentation (Desmond et al. 2015, Tait 2019, Blain et al. 2021).

4.2.4 Autonomous surface seacraft

An increasing number of surface-operating autonomous vessels are becoming available to observe and monitor the marine environment. Autonomous or Unmanned surface vehicles (ASVs, USVs) like Saildrone[33] or wave gliders[34] are becoming the 'eyes on the ocean' for a range of science, defence and commercial applications. These systems are designed for large-area, "open-ocean" applications rather than close to the shore because of issues with safety, collision and grounding. ASVs can be equipped with optical sensors similar to those on CTDs to map turbidity. Substantial costs savings are gained from the use of autonomous sampling (excluding the cost of the asset itself) and increase the number of observations by several orders of magnitude in a short period of time.

There is research and development into USVs in New Zealand at present, with prototype vehicle developments by Auckland-based technology company X-craft limited[35]. As part of a Smart Idea proposal to MBIE, NIWA is aiming to work with X-craft to develop small, low-cost autonomous vehicles for coastal monitoring and management. One of the key aims of such a project would be to develop an instrumented, autonomous seagoing platform that could measure and monitor suspended sediment in the coastal zone over large scales (New Zealand national scale) and long periods (decadal).

4.2.5 Autonomous subsurface capability (gliders)

Ocean gliders are autonomous underwater vehicles (AUVs) that provide high-resolution spatial and temporal observations in coastal and shelf seas. Ocean gliders use a buoyancy engine to passively sample the ocean. The buoyancy engine is an efficient means of locomotion and means a glider deployment can have a duration of 4-6 weeks, collect thousands of profiles and can cover more than 500km (horizontally) of ocean sampling. Final versions of recent New Zealand glider data provide vertical bins of 1m and have an average horizontal along-track resolution of 0.5 km. The long-duration of missions mean that ocean gliders are well-suited for mapping coastal processes including sedimentation at the days to weeks timescales.

Instrumentation on ocean gliders can include CTD, turbidity, and CDOM sensors. These are equivalent parameters to CTD profiling instrumentation albeit in more compact versions for fitting into the smaller glider science platforms. Bio-optical sensors (Table 4-1) can also be used on AUVs. In particular, a transmissometer and multi-spectral backscatter sensor are now also fitted to the NIWA glider system. Data from autonomous sampling platforms can have issues with calibration-drift, since *in situ* calibrations can only be obtained from samples at the start or end of a month-long mission. Also, biofouling can affect data quality during extended operation of optical sensors on subsurface vehicles. In the worst case, this limitation means that observations from gliders are relative and provide patterns rather than absolute concentrations of properties.

Smaller, subsurface AUVs are being developed to increase data and knowledge in coastal systems. Improving affordability of AUVs is also an important factor in new AUVs. Of particular note for New

[33] https://www.saildrone.com/
[34] https://www.boeing.com/defense/autonomous-systems/wave-glider/
[35] https://www.x-craft.co.nz/

Zealand is the ecoSUB[36] developed and designed in partnership with the National Oceanographic Centre, UK. The ecoSUB is intended for short-term observations with sensor packages are similar to other tools being used in New Zealand Territorial Seas and EEZ. A tool like ecoSUB would provide the ability to map peak coastal sedimentation after storm events, both at the surface to connect to NIWA-SCENZ products and subsurface to quantify vertical near-field scales.

4.3 Automated river monitoring

The majority of sediment transport in rivers and streams occurs during storm runoff events, therefore (McKergow & Hughes, 2010) recommended that storm sampling be the focus of any monitoring programme that aims to quantify change in the input of sediment to the coastal zone over time. Changes in sediment flux into the coastal zone in rivers can be detected by measuring suspended sediment concentration (SSC) or suspended sediment load (SSL) in rivers over time. Concentrations and loads may alter by (1) changes in the mean concentration or load, (2) changing variability in concentration or load, (3) changes to the concentration or load maximum or minimum, and (4) changes in the frequency of high concentrations or loads (Viaud et al., 2004; McKergow & Hughes, 2010).

Continuous monitoring (i.e. using automated sensors) on New Zealand rivers are operated by various agencies, including regional councils, NIWA, hydro-power operators (e.g. Genesis NZ). The measurements allow long-term patterns of sediment supply to be estimated. For example, the updated sediment load estimator for New Zealand was calibrated using measured sediment loads at 273 sites as detailed in Hicks et al. (2019, appendix D): "The dataset used is a composite of past and present national networks, regional networks, hydro-power company networks, and miscellaneous individual site studies. There is currently no national suspended sediment monitoring network but most regional councils (notably Horizons, Environment Waikato, Environment Southland, Auckland Council, and Greater Wellington) now operate their own network of sites where the focus is on measuring suspended sediment loads during runoff events, typically either by using auto-samplers, turbidity sensors, or both. A common motivation is to determine long-term average load, but there is also interest in annual loads and event loads (e.g., see Hicks 2018, Hicks & Hoyle 2012). It is anticipated that these existing regional council networks will standardise their data acquisition and load calculation methods to those detailed in the soon-to-be-released National Environmental Monitoring Standard (NEMS) for river suspended sediment load (Hicks 2019)."

Radiometric sensors from bridges could also potentially be used to monitor changes in particulate material in rivers (see Section 4.1).

4.4 Vessel-based sampling

Sampling from vessels includes: (1) underway sampling (where water from an inlet on the hull is pumped onboard continuously) for continuous analysis, or by towed instrumentation containing instruments; (2) deployments at station with electronic instrumentation; (3) collection of water samples that are subsequently analysed in the laboratory.

4.4.1 Underway sampling

Bio-optical properties can be measured over relatively large areas using underway sampling from vessels. Methods include towing equipment behind a vessel (e.g. the "BioFish", Gall, 2003; Figure 4-3), or pumping water onboard where the water can be analysed by a suite of equipment or sampled

[36] https://www.ecosub.uk/

for subsequent laboratory analysis. A complex set of equipment, including for measuring optical basckscatter, absorption and attenuation, is fitted to the research vessel (RV) Tangaroa (Figure 4-4), but a simpler approach could be used for smaller research vessels, or ships of opportunity (like ferries or fishing boats) for routinely measuring suspended sediment in the coastal zone.

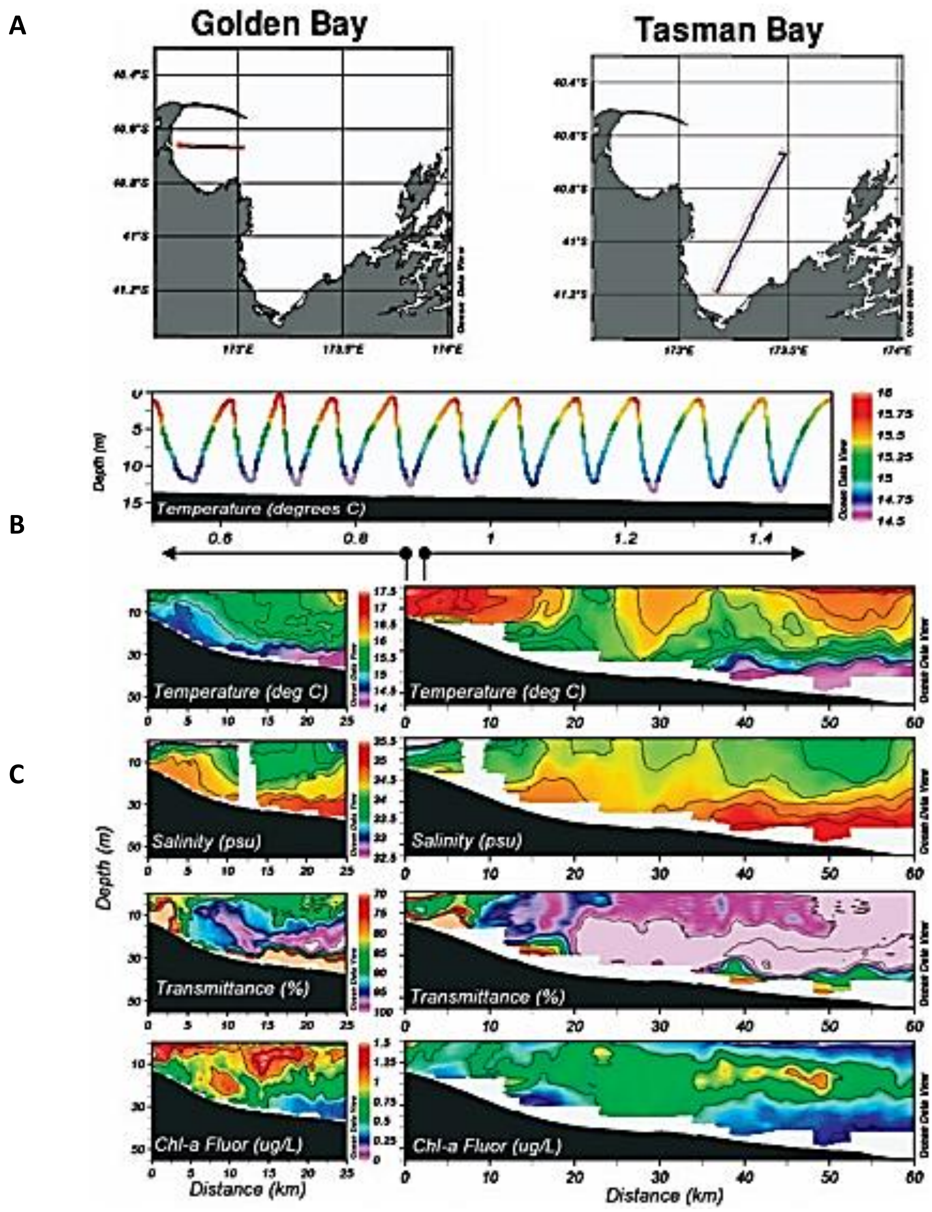

Figure 4-3: Underway bio-optical sampling by the BioFish. BioFish flight paths in Golden Bay and Tasman Bay in December 2001. The BioFish is an undulating, towed instrument which measures water temperature, salinity, chl-a fluorescence and optical transmittance continuously during operation. **A, B**: raw BioFish temperature data over a short sector (1.5 km) of the Tasman Bay flight path. **C**: Spatial maps over the entire flight paths for temperature, salinity, transmittance (water clarity – indicative of TSS) and chlorophyll a fluorescence (abundance of algae). Source: Gall (2003).

Figure 4-4: RV Tangaroa Underway Flow Through System (TUFTS) on voyage TAN2101. Image shows pre-screening sieves and vortex debubbler, prior to flowing through a series of in-line sensors including for attenuation and sediment backscatter. A simplified setup could be used on smaller research vessels and ships of opportunity like ferries and fishing boats. Source: O'Driscoll et al., (2021).

4.4.2 Station deployments

With regard to suspended sediment concentration, measurements at a given station usually take the form of vertical profiles of water column properties from conductivity, temperature depth (CTD) instrumentation equipped with optical turbidity sensors (see Table 4-1). Light attenuation with depth (water clarity) can also be measured to enable the intensity of light reaching the seabed to be estimated. This can be assessed using broadband (PAR[37]), multispectral or hyperspectral radiometers, or using visual-based measurements like Secchi depth[38]. Water samples can be obtained from "rosettes" of water bottles or hand-held water samplers to compare and calibrate digital turbidity data to gravimetric suspended sediment concentration (Section 4.4.3).

4.4.3 Water sample analysis

To measure the gravimetric concentration of sediment, water is filtered through a dried and weighed filter paper of known pore size (usually a glass fibre filter of 0.7 μm nominal pore size). Depending on water clarity the volume of water filtered can range from 1 to 5 litres. The suspended sediment is retained by the filter paper and is washed to remove salt, dried and re-weighed at a laboratory to determine *in situ* concentrations of particulate material. There are small errors in suspended sediment values when filtering is delayed. These data are often used to calibrate profile data. It is useful to have a range of suspended sediment concentrations for the best calibration of instrument data. Other common parameters are often taken at the same time, including temperature, CDOM

[37] Photosynthetically Active Radiation, 400 – 700 nm
[38] https://www.lawa.org.nz/learn/glossary/s/secchi-disc/

and nutrients, and the absorption spectrum of particulates can also be measured from the same samples.

Water sampling is undertaken routinely by some regional councils and DOC (marine reserve monitoring programme), and compilations of these data have been used in state of the environment reporting (Dudley et al., 2017; Dudley & Jones-Todd, 2018). These analyses highlight that: (1) it is crucial to co-ordinate methods and protocols for water sampling and laboratory processing across agencies for the data to be useful at a New Zealand national scale (hence NEMS developments); (2) the value of this kind of sampling for the purpose of tracking long-term change is limited because the number of samples is small (monthly sampling from a relatively few sites) and the space-time variability is large; (3) sampling is focussed very close inshore and does not cover the Territorial Sea scale; (4) the *in situ* data are potentially useful for investigating changes seen in the satellite, but this analysis requires further development – see Section 3.7). Satellite data can be very useful for complementing or prioritising the space-time scale of this water sampling programme, for example by putting these *in situ* monitoring data in a coastal-shelf scale context (see Recommendations in Section 7.5.4).

4.4.4 Survey design and scale

In terms of being part of a monitoring system for coastal sediment, vessel-based sampling has pros and cons. It provides highly accurate (i.e. within a few percent absolute accuracy) of suspended sediment concentrations but it is resource intensive, and very localized in time and space. Typically, the small-scale variability in water samples is not assessed. For example, if three samples are taken in quick succession, how different are they on average? If multiple samples from a given point vary by more than a few percent, the high accuracy of the laboratory method is of little importance compared to characterizing the variability on larger time and space scales. In other words, it is necessary to investigate the scale dependence of *in situ* measurements (Section 3.5) to understand how to use them appropriately.

Water sampling can be carried out by hand (“bucket sampling”) from piers, jetties, harbours, or even by wading out from beaches, but this only provides information very close to shore. In shallow environments, the samples may be contaminated by material that has been resuspended from the seabed by the collection process. To sample further away from the shore, a vessel is needed, though other methods (like drones or helicopters) are possible and can be cost-effective. Vessel- or aerial-based sample collection on a grid pattern would permit an understanding of suspended sediment over an extended area like a coastal harbour or region.

Collection and analysis of water samples for sediment is expensive because it requires skilled field and laboratory staff to undertake the work, and potentially a vessel or aerial platform. This means that such water sampling is usually not carried out very often, maybe once a month, which provides much fewer measurements of water properties than other tools such as continuous monitoring by immersed instrumentation. Limited process understanding comes from this approach. For the purposes of monitoring, the low number of samples means that the timeframe to establish a range of concentrations for a coastal system will be multiple years. Depending on the amount of variability compared to the size of any trend, obtaining sufficient data to enable a trend to be determined or rejected with useful statistical power is likely to take a long time, likely decades. In addition, capturing events is difficult with this approach due to constraints on field operations in adverse conditions.

As detailed in Section 3.7, *in situ* sampling and water analysis is useful to help improve satellite data however if a number of sites are sampled across the New Zealand CMA that span a range of conditions (low to high sediment concentrations; muddy sediment to refractory sediments) and if these sites are located more than 1 km offshore and chosen to have low small-scale variability.

5 New Zealand case studies

5.1 Current New Zealand research

Research on moderate-resolution ocean colour data for coastal sediment research is being carried out at serval New Zealand institutions including: NIWA (Pinkerton/Gall, this report); Cawthron Institute (Knight); Xerra Earth Observation Institute[39] (original name: Centre for Space Science Technology, Xerra was a successful applicant in the Regional Research Institutes Initiative, administered by MBIE and is now a private organisation); University of Otago[40]; Massey University[41] (with special focus on lakes); GNS[42] (with focus on terrestrial and geological applications); and Landcare Research[43] (with focus on terrestrial applications).

5.2 New Zealand case studies

In probably the first project in New Zealand aiming to locally-tune satellite processing algorithms for the coastal zone, NIWA and Environment Bay of Plenty carried out bio-optical surveys of the Bay of Plenty (Pinkerton, et al., 2004). The focus was on regional calibration of satellite-measured chlorophyll concentrations to underpin modelling and productivity assessments in the region in support of Aquaculture Management Areas (AMAs). Since then many studies have been carried out exploring the variety and potential for coastal satellite remote sensing of sediment in the New Zealand coastal zone. Some selected case studies are presented below. This selection is not exhaustive, and satellite data have also been used in other studies to characterise coastal water quality and its variability (including long-term change).

5.2.1 Canterbury Plumes

In a study for Environment Canterbury (EC; Schwarz et al., 2010), ten rivers in the Canterbury Bight, as well as Te Waihora/Lake Ellesmere, were studied using a core, cloud-free dataset of colour satellite imagery from the NASA MODIS-Aqua sensor. “Freshwater extent” was estimated wherever neighbouring river plumes could be distinguished from one another based on gradients in light scattering derived from the satellite data. The processed images were used to answer four key questions raised by EC as to the mixing and movement of freshwater (and suspended sediment) introduced into the Canterbury Bight from rivers and streams. In particular, there was interest in the extent to which river and stream inputs to the Canterbury Bight affect the water quality of the southern bays of Banks Peninsula, Akaroa Harbour, northern Banks Peninsula and Pegasus Bay.

The major findings were:

- River plumes are frequently visible in moderate-resolution satellite imagery of the Canterbury Bight.
- The plume fronts were generally constrained to within 6 km of the coastline, likely due to the Southland Current and tidal currents.
- The combined river plumes travelled a median distance of 62 ± 23 km northwards along the shoreline and eastwards around Banks Peninsula. Akaroa Harbour was

[39] https://www.xerra.nz/
[40] https://www.otago.ac.nz/surveying/research/geospatial/index.hmtl
[41] https://www.massey.ac.nz/massey/explore/research/gis/gis_home.cfm
[42] https://www.gns.cri.nz/Home/Our-Science/Land-and-Marine-Geoscience/Regional-Geology/Remote-Sensing
[43] https://www.landcareresearch.co.nz/news/smarter-remote-sensing-for-effective-land-management/

potentially affected by river water from the Canterbury Bight on 55% of the days in this analysis.

- Of the ten rivers studied here, plumes from the Waitaki, Ashburton and Pareora Rivers were seen to undertake the greatest northward excursions. Under high flow situations, the Rakaia River plume frequently merged with resuspended sediments and/or water from the Ashburton River and Te Waihora/Lake Ellesmere
- Water flowing from Te Waihora/Lake Ellesmere was more easily traced than river plume water because of its characteristic yellow/green colour, reflecting hyper-eutrophic conditions in this lake as well as high suspended sediment content. Lake water was observed up to 95 km northeast of the lake opening, up to 33 km off-shore and up to 27 km to the southwest. The dominant pattern of lake water dispersal was north-eastwards transport along the shoreline, around Banks Peninsula and into Pegasus Bay.
- Water from rivers in the Canterbury Bight could be detected as far north-east as Pegasus Bay in 40% of the days included in this analysis.

In terms of recommending future work, Schwarz et al. (2010) concluded that consideration of river flow history and watershed characteristics together with satellite data could enhance understanding of what the satellite data are showing and hence guide the use of the satellite data in assessing the impact of land run-off on ecologically sensitive coastal areas in the Canterbury Bight. These conclusions were incorporated in to Recommendations (Section 7.5.4).

5.2.2 Lyttelton Harbour

In a study for Environment Canterbury in 2014 (EC; Pinkerton et al., 2014), satellite images of ocean colour were used to assess the spatial and temporal patterns in TSS in waters of Lyttelton Harbour / Whakaraupō and Port Levy / Koukourarata. In this study, *in situ* measurements from EC water quality monitoring were augmented with data from NIWA based on the NRWQN[44] in order to "locally tune" satellite processing methods in order to improve the accuracy of maps of TSS. Specifically, the relationship between turbidity and TSS in the Waimakariki from EC sampling were shown to be consistent with the relationship derived from the NRWQN data across New Zealand. Then, the relationship between turbidity to TSS in Lyttelton Harbour from a combination of EC sampling and NRWQN data at the nearest station (CH4, mouth of the Waimakariri River) was used to convert satellite measurements of backscatter, scaled to turbidity, to a local estimate of TSS.

TSS derived from Using data from MODIS-Aqua between July 2002 and April 2014, satellite-derived TSS predictions were generated at a 250 m spatial resolution and mapped onto a grid encompassing the Lyttelton Harbour / Pegasus Bay region.

Although ocean colour satellite images are not usually used in small water bodies, this study has showed that MODIS-Aqua data can be a powerful basis for long-term observation of TSS in the middle and lower reaches of Lyttelton Harbour. The uncertainty in satellite-derived TSS cannot be estimated directly because of the difficulty in obtaining co-incident satellite images and *in situ* measurements, and because of differences in the spatial scale of the measurements. Overall, we found that:

[44] National River Water Quality Network

No valid data were obtained within about 1 km of the coast and in shallow waters at the head of Lyttelton Harbour as a result of shallow water, geolocation issues, atmospheric correction and in-water algorithm effects. However, in the centre of the Lyttelton Harbour channel, especially in the middle and lower reaches, there was reasonable satellite coverage, with most pixels being observed a few hundred times over the 11+ years of the study.

- Long-term median concentrations of TSS in the upper Lyttelton Harbour were estimated as 21 g m^{-3} using the satellite images, decreasing to 9.3 g m^{-3} near the mouth. The lower reaches of Port Levy and Charteris Bay had TSS similar to those at the mouth and upper reaches of Lyttelton Harbour respectively.
- For a given distance along Lyttelton Harbour, the variation between the 5^{th}-95^{th} percentiles of TSS derived from the satellite data was about 0.5–1.8 of the median.
- There is no indication in the satellite data that TSS over much of Lyttelton Harbour is trending up or down over the period July 2002 to April 2014.

The main recommendations arising from this study were to consider focus on measuring optical attributes *in situ* in addition to TSS, especially Secchi depth and turbidity. These measurements allow locally-tuned relationships between optical backscatter, turbidity and TSS to be developed and validated. Additional optical field measurements could include water clarity (using black disc visibility, or beam transmissometer) and backscattering (using backscattering instrument such as the Wetlabs VSF-3 or Ecotriplet). A mooring in Lyttelton Harbour with optical instrumentation would allow episodic sediment discharge events to be resolved.

5.2.3 TransTasman Resources

Satellite estimates of TSS were used to map out spatial and seasonal patterns of TSS in the South Taranaki Bight to aid efforts to understand the potential environmental effects of mining of ironsand. MODIS-Aqua data were used, and a local tuning of the algorithms was carried out (Pinkerton & Gall, 2015). Field and laboratory measurements allowed the optical properties of the sediment to be characterised for use in modelling the effects of mining on water colour and clarity. Local measurements of diffuse attenuation (from profiling multichannel radiometers), Secchi depth and beam transmission (beam transmissometer) were made in the South Taranaki Bight. Water samples were also collected and analysed in the laboratory at NIWA to determine the characteristic inherent optical properties of the material (especially the chl-specific absorption, backscatter-to-absorption ratio for sediment, and the exponents of CDOM and sediment detrital absorption).

The research showed that the ecological effects of suspended sediment can be more important at some times than at other times. In environmental impact assessment work for the TTR/ironsand mining proposal presented to the Environmental Protection Authority (Pinkerton et al., 2015; Cahoon et al. 2015) it was clear that there are naturally periods of high suspended sediment near the coast, and periods where the water is clearer. It is likely that the ecological effect of discharging suspended sediment from seabed mining into the environment would be minimised by discharging sediment during the naturally turbid periods, and avoiding discharges during the naturally clear periods so as to safeguard these periods of clarity. So, it’s not as simple as reducing the average or maximum sediment concentration to reduce ecological effects.

5.2.4 Manukau Harbour

Watercare Services Limited (Watercare) commissioned NIWA to develop the Manukau Harbour Model to better understand the impact that discharge of treated wastewater has on harbour water quality. As a supporting strand of work, NIWA was commissioned to investigate use of satellite data (ocean colour and infra-red images) to assess water quality in Manukau Harbour and to assist with future monitoring (Pinkerton, 2017).

Data from the NASA MODIS-Aqua satellite were used to obtain remote measurements of: (1) sea-surface temperature (SST); (2) total suspended solids concentration (TSS); (3) chlorophyll-a concentration (chl); and (4) water clarity. This study obtained more than 1000 cloud-free images of the region during the 15 year period (June 2002 to February 2017). Each complete satellite image of Manukau Harbour contained more than 3000 measurements at a resolution of ~500 m.

Local tuning of the SST satellite algorithm was not needed, but substantial local tuning of the optical algorithms was required. The relationship between backscatter and turbidity at the three NRWQN sites closest with Manukau Harbour was shown to be consistent with that from the whole NRWQN dataset, and the latter was hence used to estimate turbidity from satellite-derived estimates of backscatter. Local measurements of the relationship between turbidity and TSS in Manukau were significantly different from those in NRWQN and hence these local data were used to estimate TSS from turbidity in Pinkerton (2017). End-to-end matchups with satellite data showed no significant bias in the satellite data but the proportion of variance explained was low (10%).

The existence of considerable *in situ* information made this tuning possible. The satellite data were used to investigate trends in TSS, chl and water clarity over the period June 2002 to February 2017 inside and offshore of Manukau Harbour. Satellite data developed by this project was also used to estimate the climatological (long-term average) intensity of light reaching the seabed in Manukau Harbour, which is need to model primary production by benthic microalgae.

5.2.5 South Taranaki Bight river plumes

An MBIE Envirolink project sponsored by Horizons Regional Council (O'Callaghan, 2020) looked at spatial and vertical distributions of South Taranaki Bight river plumes were observed from an ocean glider. In spring 2019, 6196 profiles over 4-week mission were obtained using an instrumented underwater glider, and these were analysed in parallel with ocean colour satellite images of surface conditions (Figure 5-1). Key sensors carried by the glider were water temperature, salinity, CDOM fluorescence, oxygen saturation, chlorophyll-a fluorescence, and particulate backscatter in the red part of the spectrum (700 nm) to qualify inorganic particulates (Figure 5-2).

The study found that river plumes with elevated organic matter concentrations were present offshore in two (of the three) major rivers in the Horizon Regional Council CMA. The vertical extent of the low salinity water varied from between 5 to 35 m below the surface. The horizontal extent of Regions of Freshwater Influence (ROFI), identified by salinity less than 34.6 psu, ranged between 3 and 11 km. ROFIs observed were both surface intensified features constrained to the upper 5m as well as features that occupied the full water column down to 35m. ROFIs were evident offshore from the Rangitīkei, Manawatū, Otaki and Waikanae rivers. Mean flow in South Taranaki Bight to the southeast and periods of strong wind mixing could, at times, enhance the horizontal transport through the region.

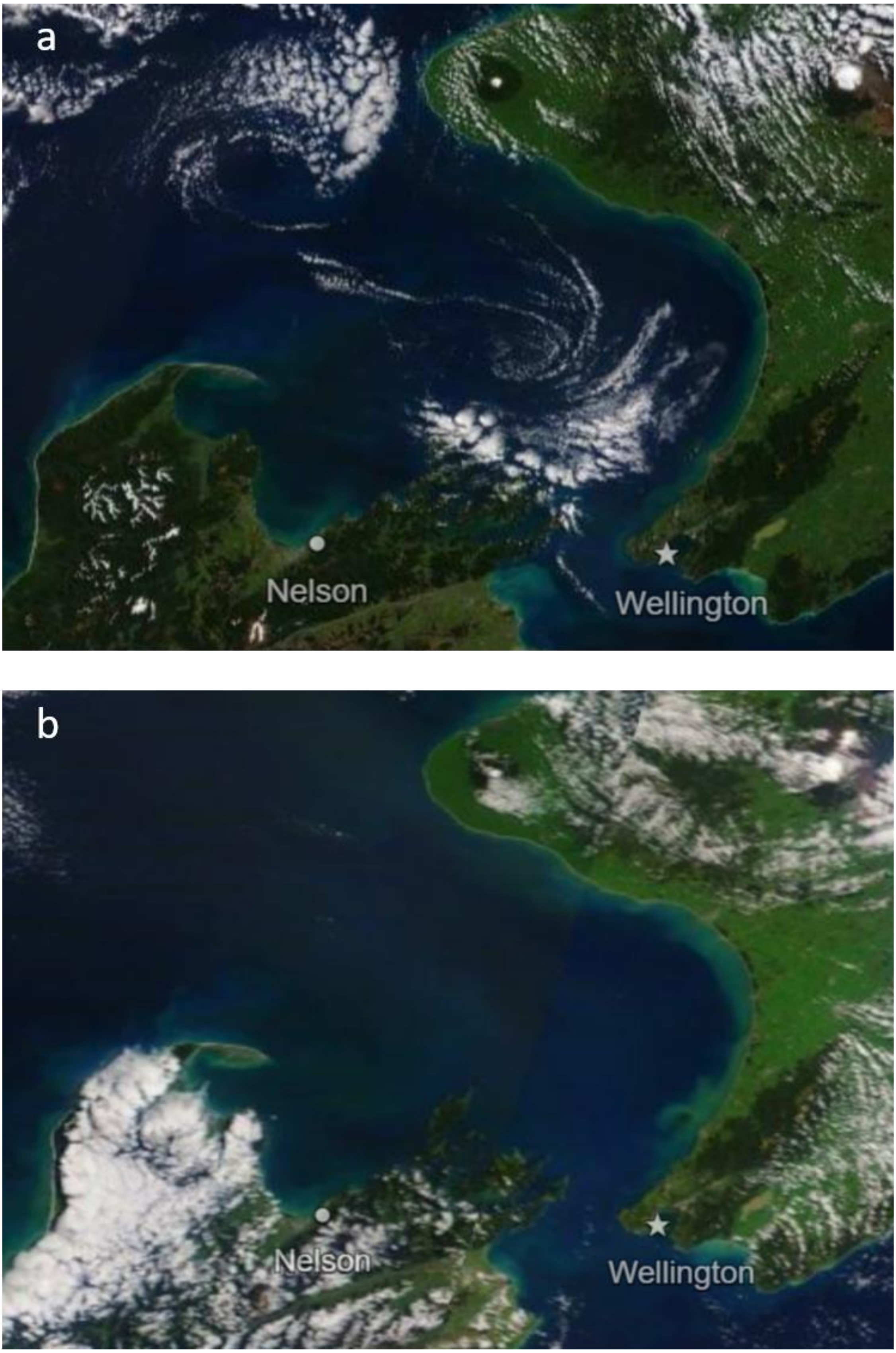

Figure 5-1: Satellite images of river plumes in the South Taranaki Bight. MODIS images from a) September 20 and b) October 6, 2019 showing the absence and presence of plumes in the South Taranaki Bight during the glider mission. Source: O'Callaghan (2020).

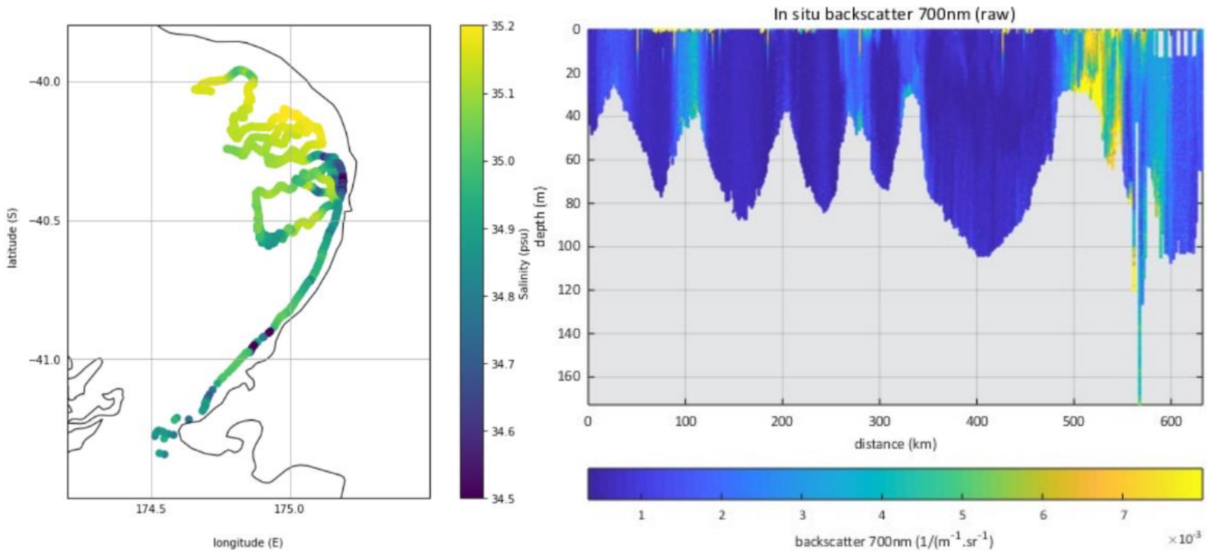

Figure 5-2: Glider data showing sediment in river plumes in the South Taranaki Bight. Left: Glider track showing salinity at 5 m with river plumes conspicuous as regions of low salinity. Right: Subsurface red-wavelength backscatter with high values indicating sediment-rich river plumes. Source: O'Callaghan (2020).

5.2.6 Waikato - river plumes

Hunt & Jones (2020) used a combination of idealised modelling and satellite imagery to assess the dispersal of estuarine plume water and suspended material throughout the west coast of the central North Island (Manukau to Kawhia). The idealised modelling was used to elucidate the relative importance of oceanographic and meteorological conditions in controlling the horizontal structure of the estuary plumes, and then compared to plumes visible in satellite imagery (Sentinel-2) and environmental monitoring data (river and tidal flows; wind-speed). The study was able to investigate under which conditions material discharged from the estuaries dispersed widely or remained close to shore. For example, it found that under low to average river flows the plumes can be categorised as either non-rotational or rotational. Rotational plumes were found to be directed southwards under light winds and northwards under stronger winds. Non-rotational plumes remained close to the estuary mouth. The type, orientation and extent of the plumes have implications for estuarine flushing and for the dispersal of land-derived contaminants into the marine environment.

In this study, a few high-spatial resolution satellite images were compared to modelled plume behaviours as validation of the characteristic modes of behaviour of plumes seen in the modelling. No estimation of water constituents was required as the focus was on spatial patterns. This case study demonstrates the utility of using appropriate satellite images in conjunction with numerical modelling and *in situ* sampling.

5.2.7 Wellington Regional Integrated Buoy Observations Programme (WRIBO)

Te Whanganui-a-Tara/Wellington Harbour is a nationally significant harbour valued for the range of ecosystem goods and services it provides. Like other coastal environments surrounded by urban areas, the harbour receives inputs of sediment, nutrients and other contaminants from the surrounding catchments. Such contaminants have the potential to adversely impact ecosystem health. Greater Wellington Regional Council (GWRC) and NIWA have been collaborating on the monitoring of Te Whanganui–a-Tara since 2016. As part of this collaboration, the Wellington

Regional Integrated Buoy Observations (WRIBO[45]) was deployed in Wellington Harbour, southeast of Somes Island in 2017. WRIBO delivers real-time, publicly available data on currents, waves, wind, salinity, temperature, sediment, oxygen, and chlorophyll. The buoy is positioned within the plume of the biggest freshwater inflow into Wellington Harbour, the Hutt River, to help make links between freshwater and marine environments and to assess the impacts of land-based activities on water quality.

As WRIBO was intentionally deployed in the pathway of the Hutt River plume, data reports (e.g. O'Callaghan, 2018, 2020) and indicate strong riverine signals. To date, the data have shown that plume thicknesses are typically surface-focused and often less than 5 m in depth. We see that ocean currents are modulated by river flows for weeks after discharge events and that river plumes influence ecosystem responses such as algal blooms. Comparisons between *in situ* sampling for TSS and time series observations from WRIBO are characteristically difficult because of mismatches in the time and space scales of sampling, and research on this continues.

5.2.8 Relative environmental suitability (habitat) modelling

Satellite data has been widely used in New Zealand and overseas to understand the spatial distribution of organisms including macroalgae (seaweed), zooplankton, benthic invertebrates (including corals), fish, seabirds and marine mammals. For example, a spatial risk assessment was undertaken for Hector's dolphins (*Cephalorhynchus hectori*) and their closely-related sub-species Māui dolphin (*Cephalorhynchus hectori maui*), to inform a revised Threat Management Plan for the species (Roberts et al., 2019). Their approach required information on the overlap in space and time between the preferred habitat of the dolphins and fishing. Patterns of turbidity are known to affect distributions of Hector's and Māui dolphins (MacKenzie & Clement, 2014) and so Roberts et al. (2019) used satellite-derived data to generate seasonal (summer or winter) maps of "relative environmental suitability" as a proxy for spatial abundances. Satellite estimates of turbidity and water clarity were used alongside remotely-sensed information on chl-a (as a proxy for phytoplankton biomass and primary production) which provides information on energy input to the base of the food-web. These maps covered all New Zealand to a bathymetric depth of up to 250 m. Because satellite-derived turbidity estimates were often missing close to the shore or in small estuaries, Roberts et al. (2019) spatially-smoothed the available satellite data near the coast. (An improved version of this inshore extrapolation was subsequently developed and used in the present report; see Section 6.2.3.) Similar habitat (relative environmental suitability) modelling for a wider range of New Zealand cetaceans was developed by Stephenson et al. (2019, 2020) which also found turbidity, diffuse attenuation (as a proxies for visual clarity) and chl-a were primary drivers of cetacean environmental preference.

5.2.9 Landsat

Data from Landsat satellites have been used for some time to observe land colour, and has more recently been explored for estimating coastal TSS. Landsat is a series of space missions, and has used different sensors over time: Landsat 1 through 5 carried the Landsat Multispectral Scanner (MSS); Landsat 4 and 5 carried both the MSS and Thematic Mapper (TM) instruments; Landsat 7 uses the Enhanced Thematic Mapper Plus (ETM+) scanner; Landsat 8 uses two instruments, the Operational Land Imager (OLI) for optical bands and the Thermal Infrared Sensor (TIRS) for thermal bands. As of 26 August 2021 all Landsat (4-8) Collection 2 data are online at Google Earth Engine. Although methods have been developed for atmospheric correction of Landsat data over the land (e.g.

[45] https://www.gw.govt.nz/annual-monitoring-reports/

Vermote et al., 2016) methods are not yet established for atmospheric correction over water. However, prototype methods are available (e.g. Pham et al., 2018; Pahlevan et al., 2021) and Landsat has been used to map the occurrence of lakes and reservoirs in New Zealand (Nguyen et al., 2019), investigate their water clarity and constituents (e.g. Allan et al. 2015; Allan 2016; Lehmann et al. 2018, 2019) and investigate river colour which is related to sediment load (Gardner, et al. 2021). Roy, et al. (2016) demonstrate that there are small, but potentially significant differences between the spectral characteristics of Landsat ETM+ and OLI, depending on application. This suggests that harmonising Landsat datasets would be important in the context of using it to track TSS in the New Zealand CMA. A harmonised Landsat dataset would give a long time-series, and allow us to generate time composites to reduce the effects of missing observations.

6 National-scale assessment of long-term trends in coastal sediment

6.1 Aim

The aim of this part of the work is to use the satellite data behind NIWA-SCENZ to identify the key places of change, over 18 years, in suspended sediment (including concentration and water clarity), and to begin to relate these changes to the physical characteristics of these key places; e.g. river mouths and other coastal areas, and exposed versus sheltered locations. Out of scope for the project is a detailed analysis of the causes of any trends observed.

6.2 Methods

6.2.1 Data source

Satellite data used in this analysis were taken exclusively from NASA's Moderate Resolution Imaging Spectrometer of the Aqua satellite[46]. The MODIS-Aqua dataset provides the longest, highest-quality and consistent spatial data set at an appropriate spatial (500 m) and temporal resolution (daily overpasses) available to date. MODIS-Aqua data have spatial resolution of 250–1000 m in visible spectral bands, frequent overpasses (daily), and long-term tracking to characterise long-term change in sensor sensitivities. We analysed data from MODIS-Aqua between July 2002 and June 2021.

Using overlapping data from multiple different satellite sensors has the potential to improve data quality and reduce uncertainty compared to using a single source. However, because of continual improvements in sensor technology, blending data from older sensors risks reducing the quality to the "lowest common denominator". Specifically: (1) the historical sensors CZCS and SeaWiFS have significantly lower spatial resolution (>4 km) than MODIS-Aqua which makes them unsuitable for coastal use; (2) MODIS-Terra radiometric sensor characterisation and stability are much poorer than MODIS-Aqua; (3) The period of operation of MERIS is almost entirely overlapped by MODIS-Aqua; (4) Long-term, high spatial resolution visible-band satellites (such as Landsat, Sentinel) are to date either of too short duration and/or have insufficient spectral bands or absolute radiometric accuracy to be suitable to detect long-term change. Hence, MODIS-Aqua data alone was used here.

6.2.2 Data processing

Level 1A (top of atmosphere, uncalibrated) MODIS-Aqua data were acquired either by file transfer from NASA (data between 2002–2007) as full spatial-resolution 5-minute granules, or as direct broadcast data by the NIWA X-band receiver (after 2007). All direct broadcast data were calibrated and processed using NASA Collection 6 calibration files. Using NASA's SeaDAS v7.2, data were rejected for land, cloud cover, solar glint, white-cap reflection, atmospheric correction failure or in-water algorithm failure. Satellite data products were calculated at a spatial resolution of 500 x 500 m and derived variables were projected to a transverse mercator grid covering the New Zealand territorial waters. The Chatham Islands were not included in the analysis to data and so are not considered in this report. We intend to include the Chatham Island region in future versions of NIWA-SCENZ.

Processing of ocean colour satellite data for TSS, chlorophyll-a (chl-a) and CDOM in the coastal zone remains scientifically challenging and is still an area of active research in New Zealand and elsewhere

[46] https://oceancolor.gsfc.nasa.gov/data/aqua/

(Siegel et al., 2000; Babin et al., 2003; Pinkerton et al., 2005, 2018). Simple empirical methods (e.g. O'Reilly et al. 1998) can work well in ocean waters but typically perform poorly coastally (IOCGG 2000; Pinkerton et al. 2006). Simple empirical adjustment of open-ocean products has been attempted around New Zealand (Jiang et al., 2017) but is of limited utility outside areas with substantial *in situ* data and if bio-optical conditions change. Instead, turbid-water atmospheric correction and semi-analytical inversion algorithms offer a more reliable approach to estimating chl-a in coastal zones (IOCCG, 2000; Ruddick et al., 2000; Lee et al. 2002; Lavender et al. 2005).

Satellite measurements of chl-a in the New Zealand coastal zone obtained by different processing methods were compared with *in situ* measurements (Dudley et al., 2017; Dudley & Jones-Todd, 2018) to test two coastal atmospheric correction methods and two types of semi-analytical in-water algorithms: (1) NIR-short-wave infrared radiation (SWIR) switching algorithm (Wang & Shi, 2007); (2) MUMM atmospheric correction model with the default MUMM alpha for MODIS of 1.945 (Ruddick et al., 2000); (3) the Quasi-Analytical Algorithm (QAA) algorithm (Lee et al. 2002; Lee et al. 2009); (4) the Garver-Siegel-Maritorena (GSM) algorithm (Garver & Siegel 1997; updated processing). MODIS-Aqua visible-band data were interpolated to 500 m using paired bands where necessary (Franz et al. 2005).

Based on our analysis (Pinkerton et al., 2019), we selected the MUMM atmospheric correction and the QAA algorithm, as this processing chain had good robustness (high number of samples), the highest R^2, lowest RMS difference, and was closest to 1:1 agreement with the *in situ* measurements (i.e. offset close to zero and slope close to unity). In a similar comparison in European coastal waters, it was found that the NIR-SWIR and MUMM methods performed similarly, but that "the MUMM algorithm gives a better quality product" (Ody et al., 2016) so our analysis for New Zealand agreed with this conclusion.

The NRWQN[47] biogeo-optical data was used to relate backscatter at 555 nm (BBP) with turbidity and thence TSS. The TSS product was defined as: $TSS = 58.00*((0.8513*BBP)^{0.8701})$. This relationship was based on a Standardized Major Axis regression between measurements of backscatter at 660 nm (ECOtriplet, Wetlabs, USA) and gravimetric measurements of TSS in many areas around New Zealand ($n=367$, $R^2= 0.928$, $p< 0.001$). The *in situ* dataset combined measurements from the Firth of Thames, Marlborough Sounds and from NRWQN.

6.2.3 In-shore extrapolation

Ocean colour satellite data is often missing for the 1-2 km closest to shore which is a problem for those particularly interested in this zone, including recreational users and coastal managers. The causes of this missing satellite data include atmospheric correction issues due to near infra-red radiance from the land, shallow water (leading to algorithm fail), and pixel geolocation errors (where a coastal pixel is mis-located further offshore by up to ~1 km). A method to extrapolate valid coastal data into this very near-shore zone has been developed at NIWA and applied to the data used in the analysis presented here. First pixels erroneously located over the land are removed. Next, the data are "despeckled", 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 applied 3 times; (2) LOESS[48]-extrapolation where the fitted variation in the property with distance offshore in 10 km-wide transects is used to estimate missing values. The smoothed and interpolated estimates are blended together using weights based on their similarity to each other and to the surrounding data. The parameters used in

[47] National River Water Quality Network
[48] Cleveland et al. 1988

this in-shore extrapolation scheme were optimised to maximise the proportion of missing data filled-in and the robustness of the values. The method works well when spatial patterns and processes further offshore are representative of the very nearshore zone (<2 km from the coast), but it cannot provide information on small-scale processes that have no offshore expression. Given that the features we are analysing in the data are of the order of >10 km, this limitation is not critical, but does highlight the need for using satellite data with a higher spatial resolution in the future to observe these very nearshore environments.

6.2.4 Deseasonalisation

Satellite data were deasonalised before trend analysis to reduce the effect of seasonal cycles on the estimates of long-term change. Monthly anomalies were calculated as the average value for each month minus the long-term monthly mean (Equation 1) in order to deseasonalise the time-series. Here, $\delta_{y,m}$ is the anomaly for year y, month m; N_y is the total number of years of data, and $S_{y,m}$ is the satellite measure for year y and month m. For example, the monthly anomaly for January 2000 was calculated as the mean of January 2000 minus the long-term mean of all Januaries. Note that this implies a reference period against which anomalies are judged as the whole time series.

$$\delta_{y,m} = S_{y,m} - \frac{1}{N_y}\sum_{y} S_{y,m} \qquad \text{[Equation 1]}$$

6.2.5 Trend-analysis

Linear trends in monthly anomalies for each pixel were determined using the Sen slope (Sen, 1968). This value is the median slope of all pairs of points in the time series. The insensitivity of the Sen slope to outliers means that it is generally the preferred non-parametric method for estimating a linear trend (Hipel & McLeod, 1994). Statistical significance was assessed using the Mann-Kendall test (Mann, 1945; Kendall, 1975) which is preferred over linear regression analysis because it is non parametric (distribution free) and does not require an assumption that the data are normally distributed.

The null hypothesis in the Mann-Kendall test assumes that the data are independent and randomly ordered (Mann, 1945; Kendall, 1975) which is not the case here. The existence of positive autocorrelation in the satellite data increases the probability of detecting trends when none actually exist, and vice versa (Hamed & Rao, 1998). A number of correction methods for autocorrelation in the Mann-Kendall test exist and we used the method of Yue & Wang (2004) which adjusts the effective number of degrees of freedom based on an analysis of the autocorrelation. After correction, linear tends were identified as significant when the Mann-Kendall P-value was less than 5%. A statistically significant trend of more than 1% of the median value is often considered meaningful (Hipel & McLeod, 1994; Scarsbrook, 2006).

6.3 Results: National Scale

6.3.1 Long-term mean values

Mean values of monthly total suspended solids (TSS) estimated from MODIS-Aqua satellite data between 2002-2020 are shown below (Figure 6-2). The monthly composites were obtained as the median of all data within the period to reduce bias associated with right-skewed (non-normal) distributions. Mean monthly values for other key variables estimated from MODIS-Aqua satellite data between 2002-2020 are also shown for comparison: SST[49] (Figure 6-2); CHL[50] (Figure 6-2); KPAR[51] (Figure 6-4); EBED[52] (Figure 6-5). KPAR is a measure of the rate of attenuation of visible light as it passes through the water, and hence shows optical 'turbidity'. High KPAR indicates high turbidity and an attenuating ("cloudy") water column, whereas low KPAR indicates optically clear water.

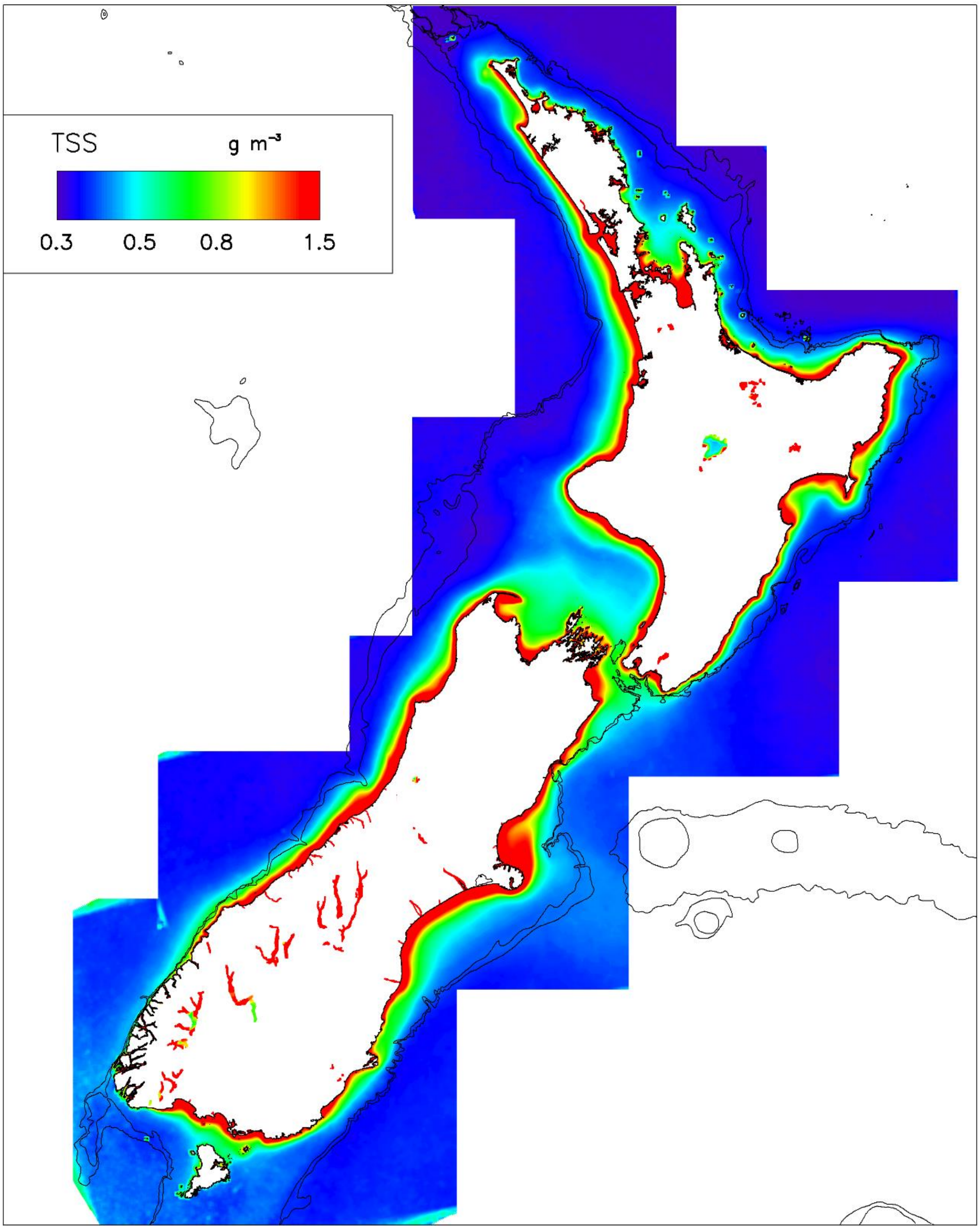

Figure 6-1: Mean values of monthly TSS (total suspended solids) from MODIS-Aqua, 2002-2021. Long-term mean values of TSS (g m^{-3}) are shown as colours (red=high, blue=low). No data or no analysis is shown white. The contours show 250 m and 500 m depth.

[49] Sea-surface temperature
[50] Chlorophyll-a concentration
[51] Diffuse attenuation coefficient for photosynthetically available radiation
[52] Light at the seabed

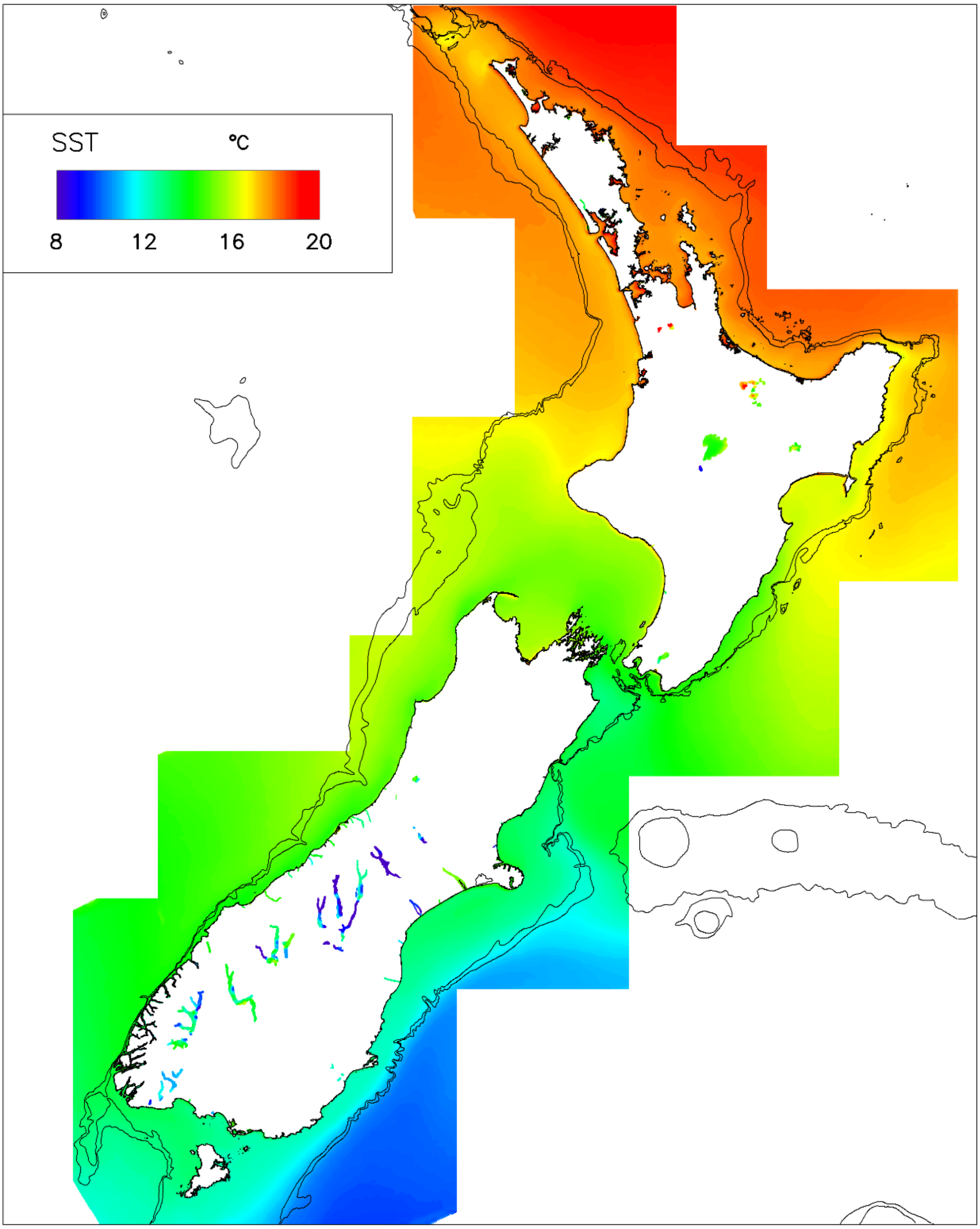

Figure 6-2: Mean values of monthly SST (sea-surface temperature) from MODIS-Aqua, 2002-2020. Long-term mean values of SST (°C) are shown as colours (red=high values; blue=low values). No data or no analysis is shown grey in both panels.

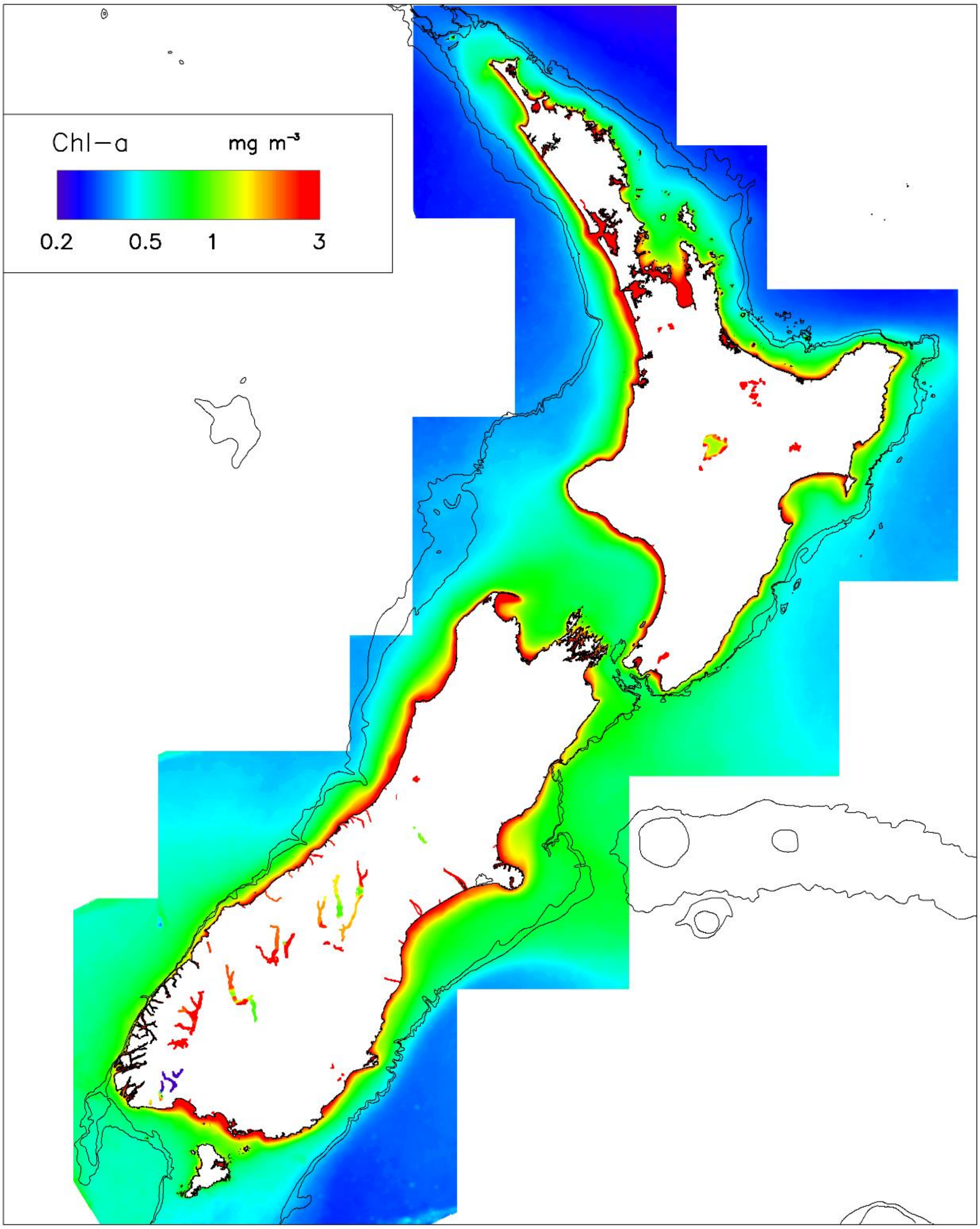

Figure 6-3: Mean values of monthly CHL (chlorophyll-a concentration) from MODIS-Aqua, 2002-2020. Long-term mean values of CHL (mg m^{-3}) are shown as colours (red=high values; blue=low values). No data or no analysis is shown grey in both panels.

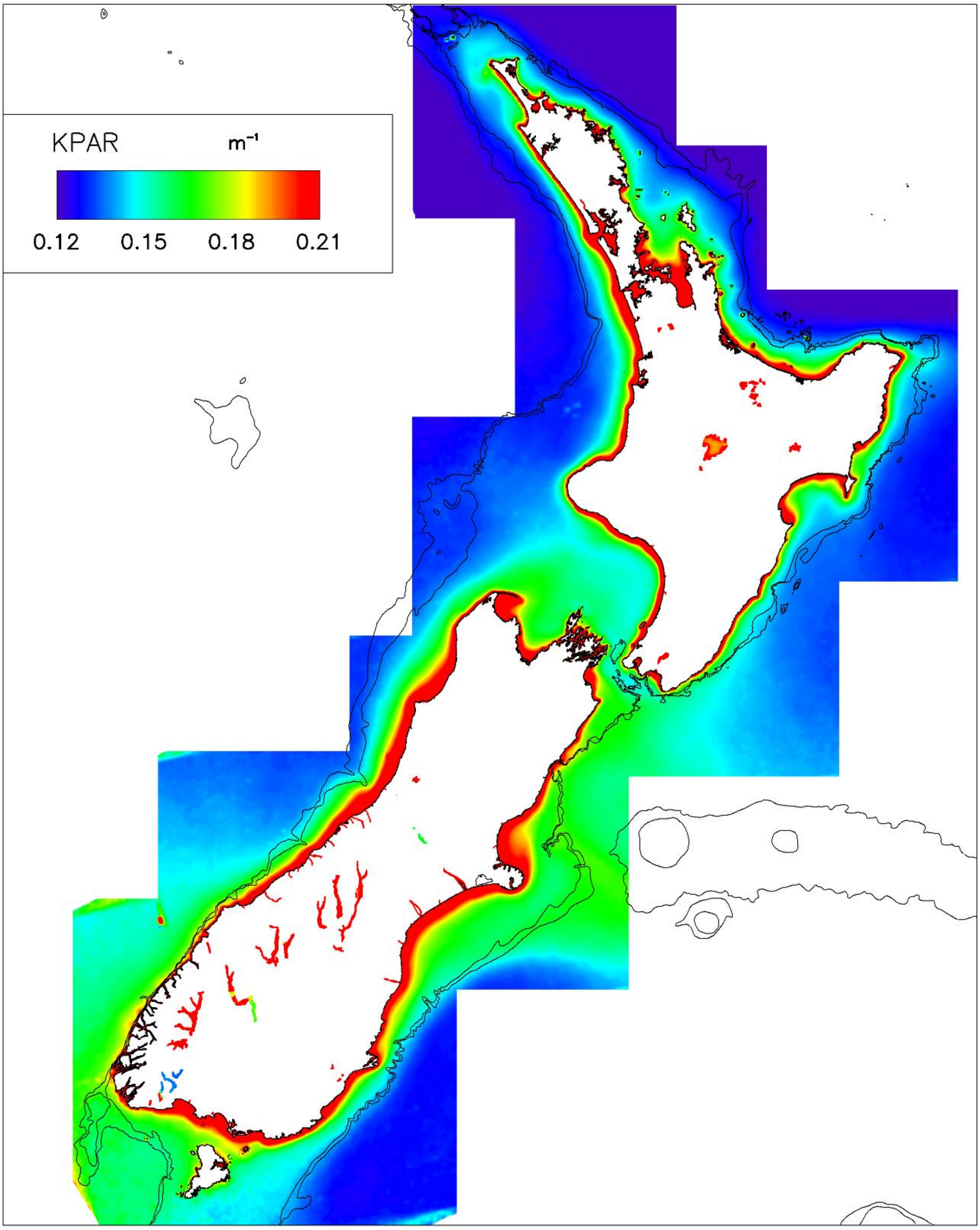

Figure 6-4: Mean values of monthly KPAR (diffuse attenuation) from MODIS-Aqua, 2002-2021. Long-term mean values of KPAR (m^{-1}) are shown as colours (red=high, blue=low). No data or no analysis is shown white. The contours show 250 m and 500 m depth.

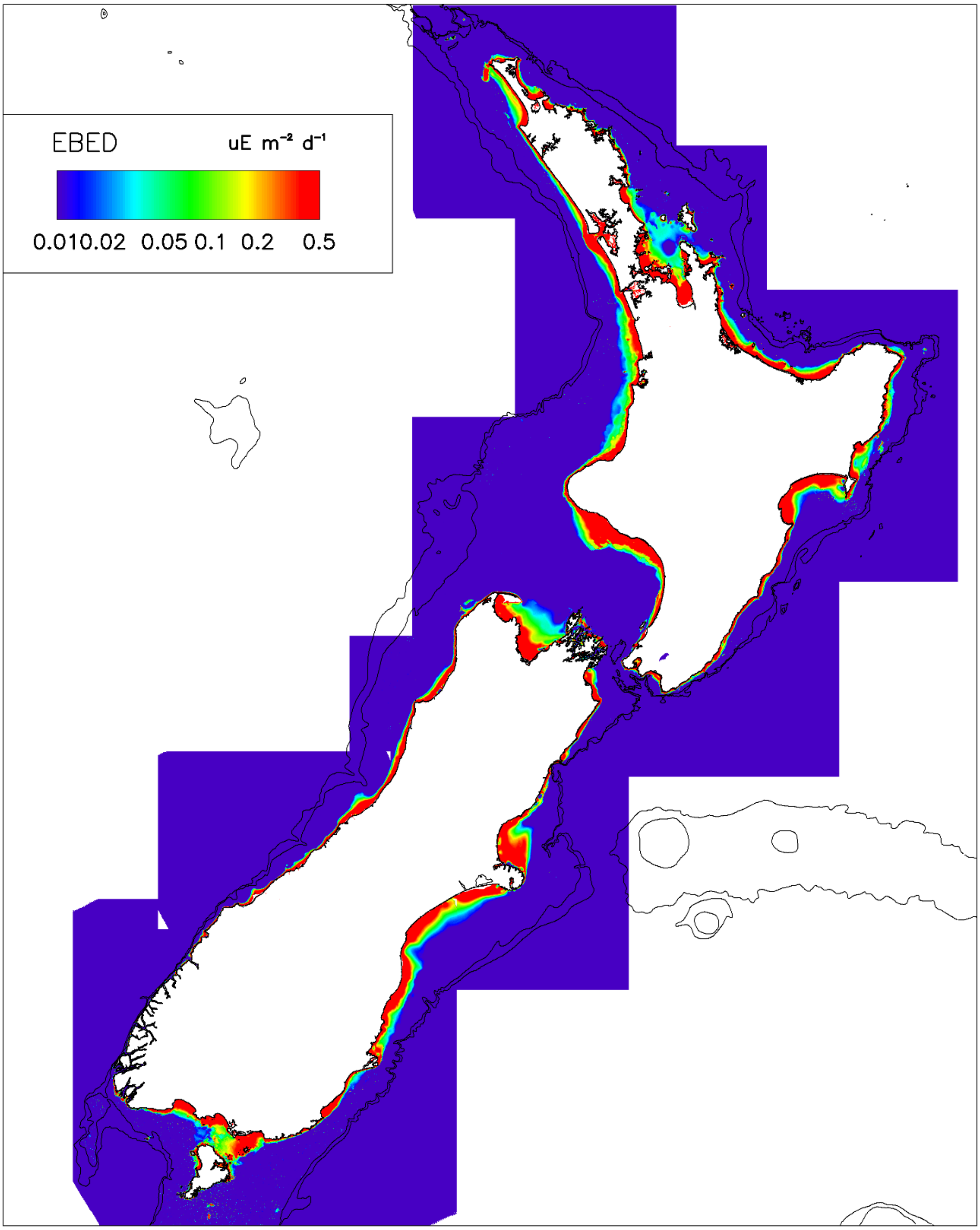

Figure 6-5: Mean values of monthly EBED (seabed irradiance) from MODIS-Aqua, 2002-2020. Long-term mean values of EBED (μE m^{-2} d^{-1} are shown as colours (red=high values; blue=low values). No data or no analysis is shown grey in both panels.

6.3.2 Linear trends

Spatial maps of linear trends in TSS estimated from MODIS-Aqua satellite data between 2002-2021 are shown below (Figure 6-6). In general, and on a broad spatial scale, largest increasing trends in TSS concentrations (> 3 mg m^{-3} yr^{-1}, about 0.3 %) are seen around coastal regions of the South Island, while most of the North Island has decreasing trends (< 3 mg m^{-3} yr^{-1}).

Spatial maps of trends in other key variables estimated from MODIS-Aqua satellite data between 2002-2020 are shown below for comparison: SST (Figure 6-7); CHL (Figure 6-8); KPAR (Figure 6-9); and EBED (Figure 6-10).

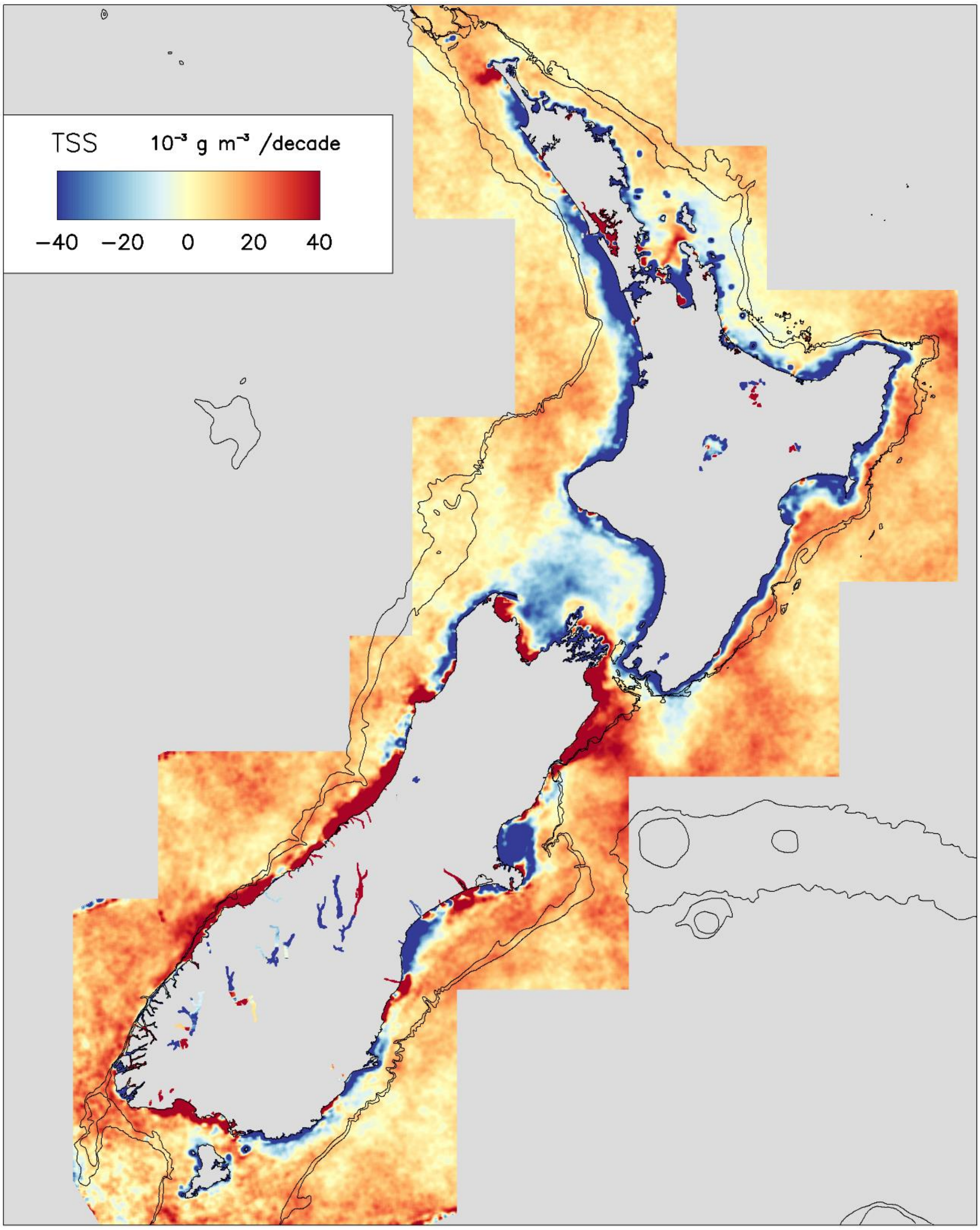

Figure 6-6: Spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. Sen-slope (linear) trends in TSS from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey. The contours show 250 m and 500 m depth.

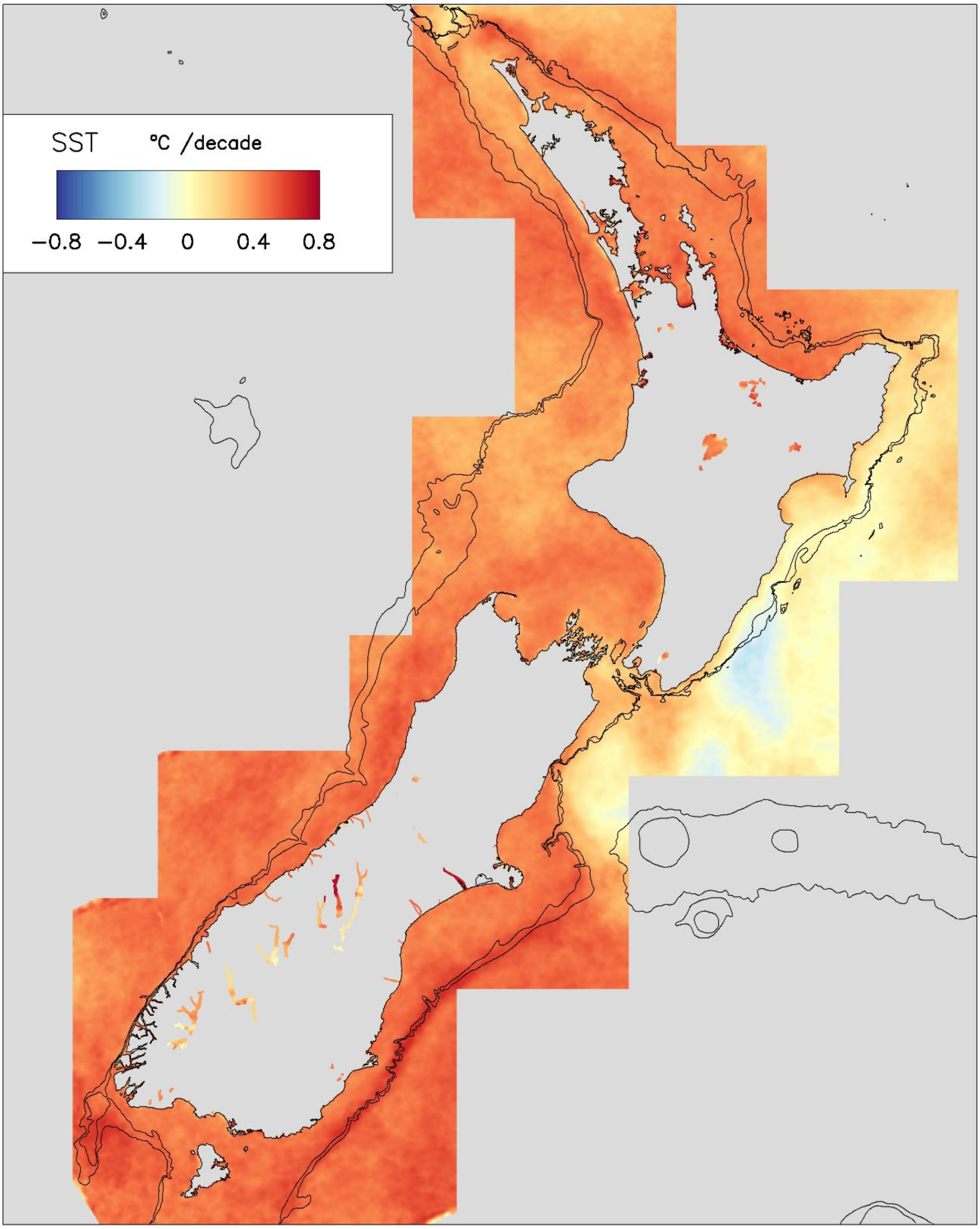

Figure 6-7: Spatial trends in monthly anomalies of SST (sea surface temperature) from MODIS-Aqua, 2002-2020. Sen-slope (linear) trends in SST from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey in both panels.

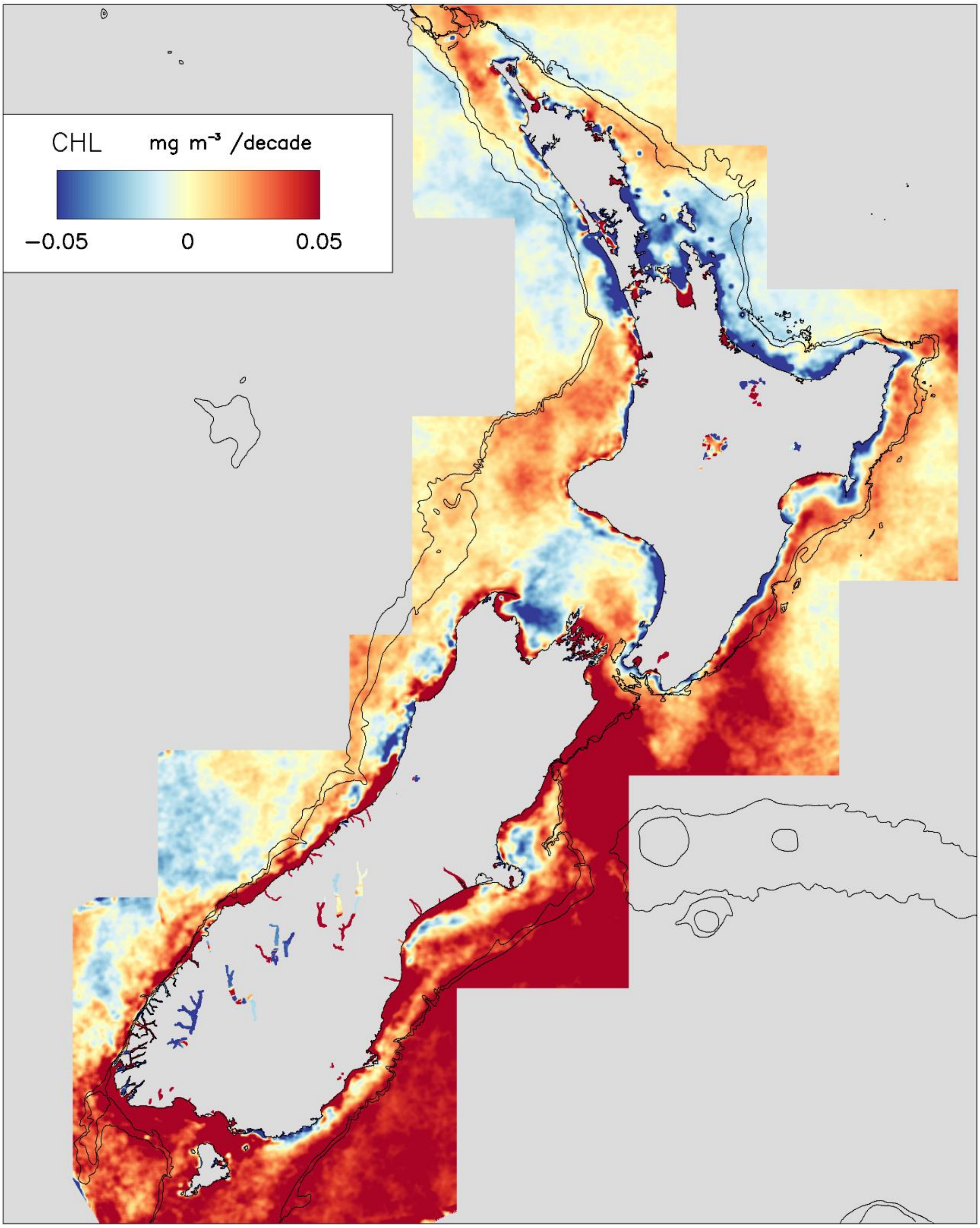

Figure 6-8: Spatial trends in monthly anomalies of CHL (chlorophyll-a concentration) from MODIS-Aqua, 2002-2020. Sen-slope (linear) trends in CHL from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey in both panels.

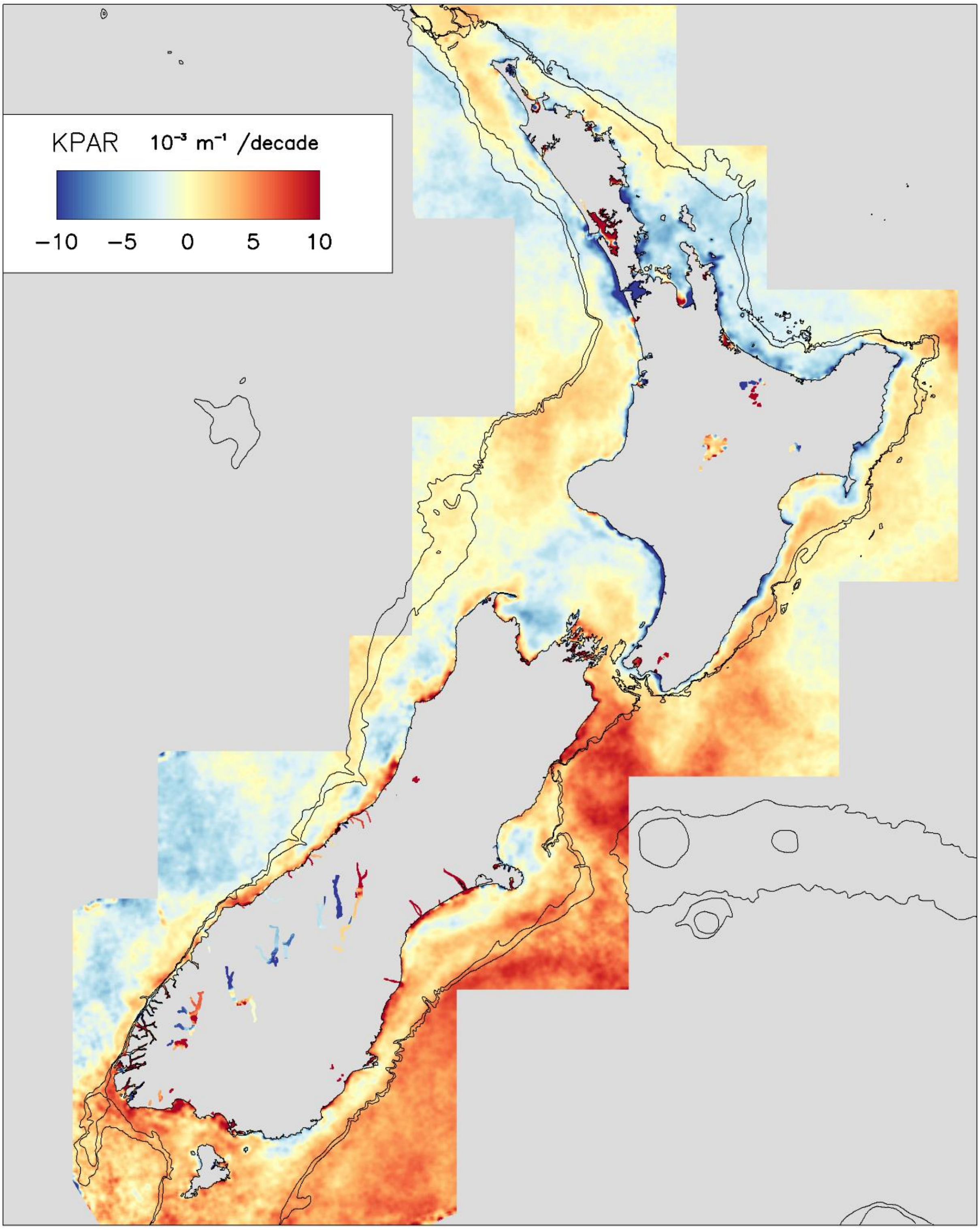

Figure 6-9: Spatial trends in monthly anomalies of KPAR (diffuse attenuation) from MODIS-Aqua, 2002-2020. Sen-slope (linear) trends in KPAR from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey in both panels.

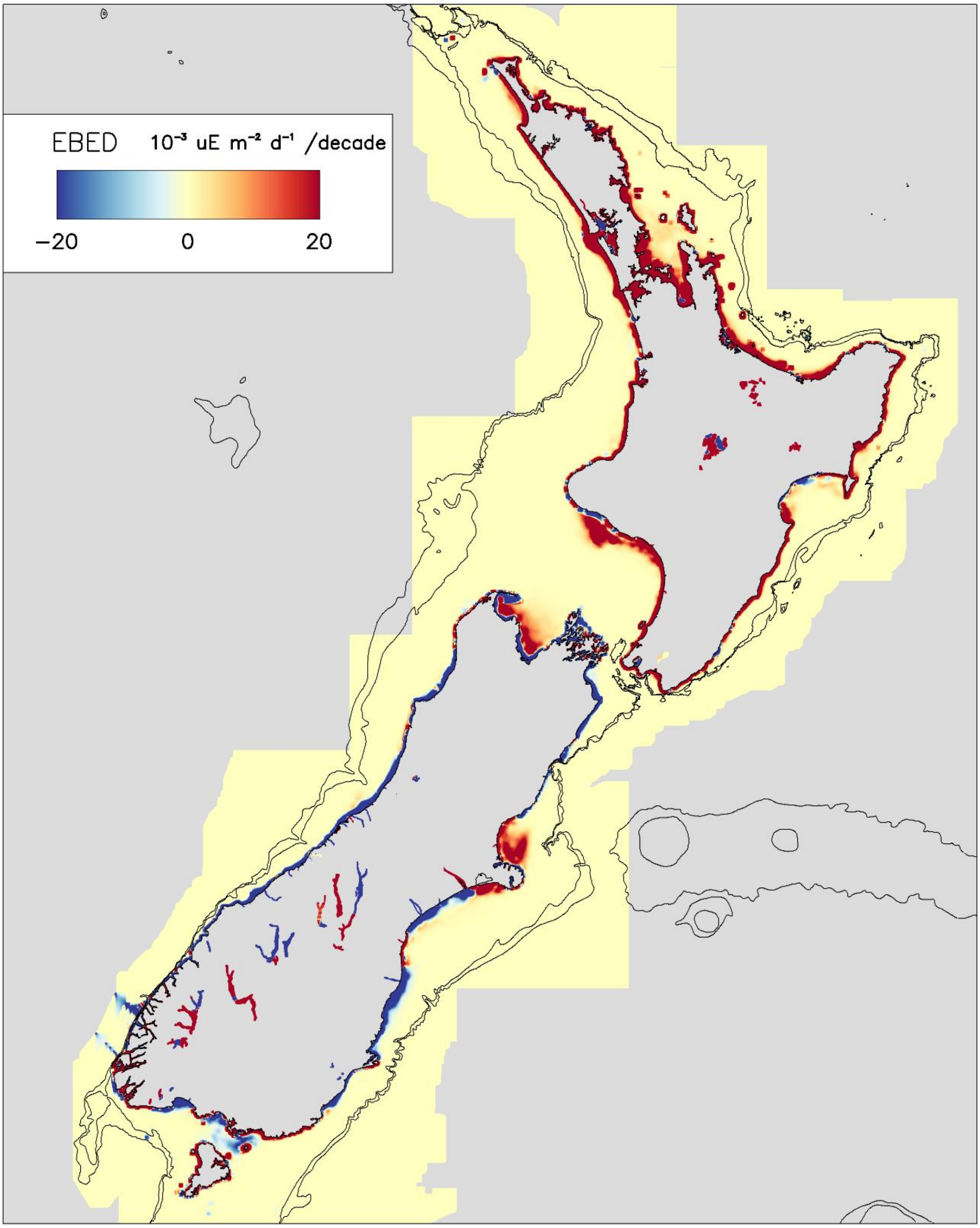

Figure 6-10: Spatial trends in monthly anomalies of EBED (seabed irradiance) from MODIS-Aqua, 2002-2020. Sen-slope (linear) trends in EBED from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey in both panels.

6.4 Results: Regional scale

A detailed examination of the causes of changes in TSS seen in the satellite data is beyond the scope of this study; definitive attribution of causes of changes will require additional data to be considered and/or new fieldwork or modelling to be carried out. In this section we provide only an initial commentary on patterns seen in the trend analysis of satellite TSS data at the regional scale and offer some preliminary suggestions of drivers. These should be considered as unconfirmed hypotheses and may be useful in suggesting priorities for study areas. Our initial interpretation of the spatial patterns in TSS trends is based on the following rationale:

- Changes to TSS that are consistent over moderate-large spatial scales (e.g. more than about 30 km alongshore or extending across the width of the continental shelf) are likely due to large-scale (climate) drivers, such as changes to phytoplankton primary production and/or changes to resuspension of sediment by currents and waves.
- Small-scale changes in TSS (of the order of less than 10s of km) are more likely due to local drivers. Where these small-scale changes are located near mouths of major rivers and estuaries, the TSS trends may be related to changes in land-use that affect material discharged by the rivers. Increases in sediment run-off and increases in nutrients (which fertilise phytoplankton production) will tend to lead to increases in TSS, and vice versa.

Spatial maps of linear trends in TSS in six regions are shown as “zoomed-in” versions of the TSS trend data shown in Figure 6-6. Locations of estuaries and river mouths can be examined using NIWA-SCENZ (Figure 6-11). The six “zoomed-in” areas are:

- Northland (Figure 6-12)
- Hauraki Gulf/Manukau/Kaipara (Figure 6-13)
- Bay of Plenty/East Cape/Hawke Bay (Figure 6-14)
- Wairarapa/South Taranaki Bight/Cook Strait/Marlborough (Figure 6-15)
- Canterbury/West Coast (Figure 6-16)
- Southland/Stewart Island (Figure 6-17)

Trends in TSS that occur near estuaries and river mouths and which appear more likely to be related to land-use changes (i.e. changes in suspended sediment, river flow and/or changes in nutrients leading to trends in phytoplankton productivity) are given in Table 6-1 and discussed in the appropriate section below.

A

B

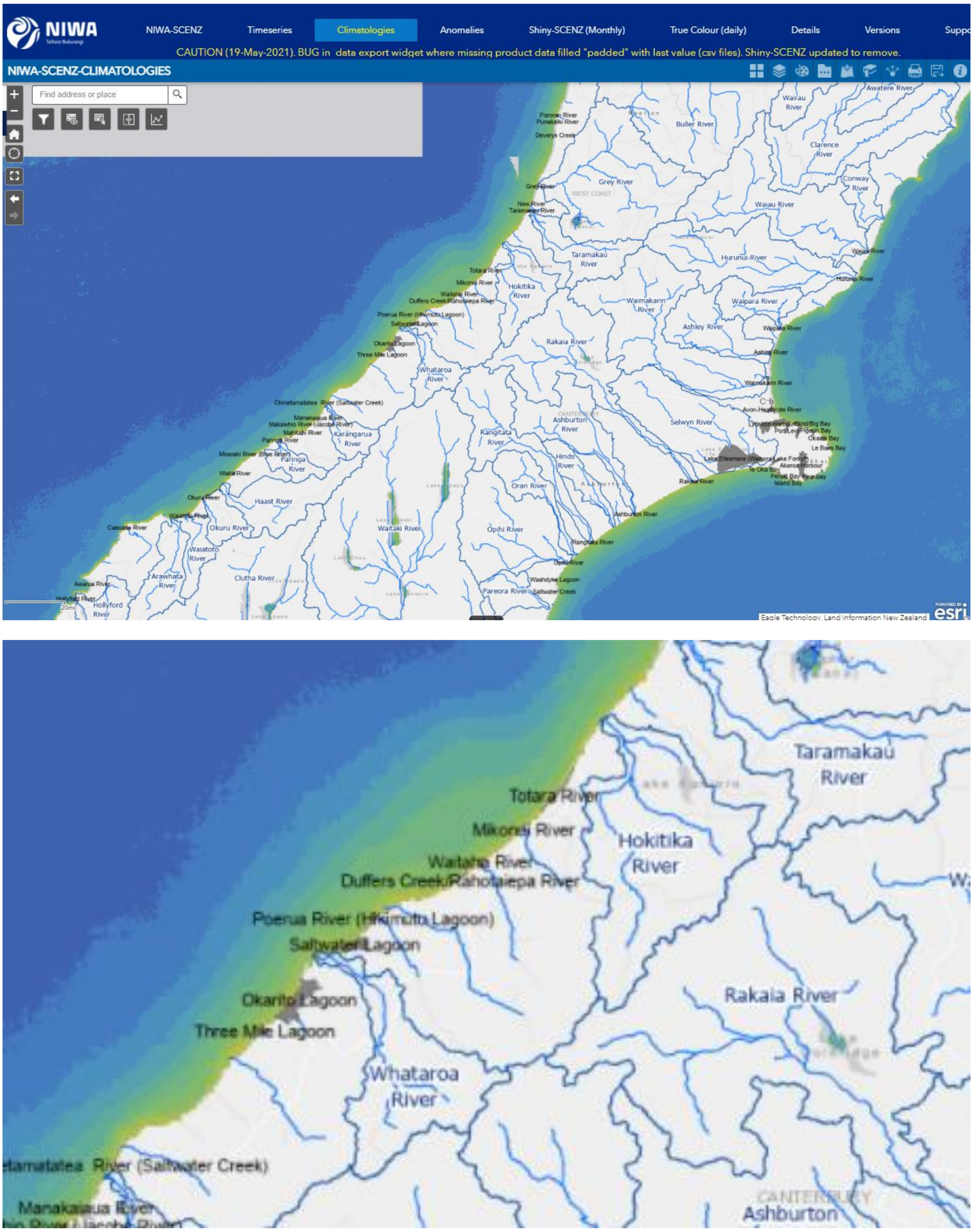

Figure 6-11: Using NIWA-SCENZ to identify where trends in TSS correspond spatially to river/estuary mouths. Two GIS-layers are added in NIWA-SCENZ: (1) NZ Estuary Classification (NIWA), black text; (2) River Environment Classification (NIWA), rivers and blue text. **A**: Showing NIWA-SCENZ screen-view, with parts of South Island; **B**: “Zoomed in” part of west coast. At present, the TSS trend layers are not available in NIWA-SCENZ, but this is recommended (see Section 7.5.2, Recommendation 3).

Table 6-1: Areas with decadal trends in Total Suspended Solid (TSS) concentration where changes seem consistent with land-use drivers on preliminary examination. See text with the figures for more details.

Location	Change in TSS	Figure
Hokianga Harbour System	Increase	Figure 6-12
Kaipara Harbour System	Increase	Figure 6-13
Waikato River	Increase	Figure 6-13
Waihou/Piako Rivers	Increase	Figure 6-13
Tamaki Strait	Increase	Figure 6-13
Tauranga Harbour System	Increase	Figure 6-14
Whakatane River	Increase	Figure 6-14
Waiapu River	Increase	Figure 6-14
Uawa River	Increase	Figure 6-14
Mohaka River	Increase	Figure 6-14
Kaupokonui Stream	Increase	Figure 6-15
Waingongoro River	Increase	Figure 6-15
Patanui Stream	Increase	Figure 6-15
Karamea River	Increase	Figure 6-15
Little Wanganui River	Increase	Figure 6-15
Mokihinui River	Decrease	Figure 6-16
Grey, New, Taramakau Rivers area	Decrease	Figure 6-16
Waiho River	Decrease	Figure 6-16
Paringa River	Decrease	Figure 6-16
Hirunui River	Increase	Figure 6-16
Waipara River	Increase	Figure 6-16
Rakaia River	Increase	Figure 6-16
Ashburton River	Increase	Figure 6-16
Rangitata River	Increase	Figure 6-16
Waitaki River	Increase	Figure 6-17
Kakanui River	Increase	Figure 6-17
Dusky Sound	Decrease	Figure 6-17
Chalky Inlet	Decrease	Figure 6-17
Tokomairiro River	Increase	Figure 6-17
Clutha River	Increase	Figure 6-17
Kakanui River	Increase	Figure 6-17

6.4.1 Northland

TSS across most of the coastline of Northland decreased between 2002-2021, likely driven by coastal warming leading to lower primary productivity (less phytoplankton-derived particulate material in the water column). However, at the northern tip of Northland (marked "A" in Figure 6-12) there is a large area of positive TSS trends for which the causes are not known. This area of increasing TSS does not appear to be associated with riverine input and is more likely of phytoplankton origin, i.e. increasing primary production perhaps because of increasing upwelling of nutrient-rich water along this coast.

The Parengarenga Harbour System has decreasing trends in TSS, as does Rangaunu Harbour, and all the harbours and estuaries down the east coast of Northland to the Hauraki Gulf including Bay of

Islands and Whangarei Harbour. The reasons for these decreasing trends of TSS are not known and could be due to reducing suspended sediment inflow in the rivers, reduced resuspension and/or reduced primary production. On the west coast of Northland, there is evidence of increasing trends in TSS associated with the Hokianga Harbour System. This trend feature is consistent with a land-use effect, such as increasing suspended sediment inflow to Hokianga Harbour or higher primary production, for example due to increasing nutrient input. Further south between Hokianga and Kaipara Harbours, there are patches of increasing trends in TSS off the west coast and it is not known if these are associated with the discharge of small rivers and streams, or are related to changes in the patterns of resuspension of benthic sediment or other causes.

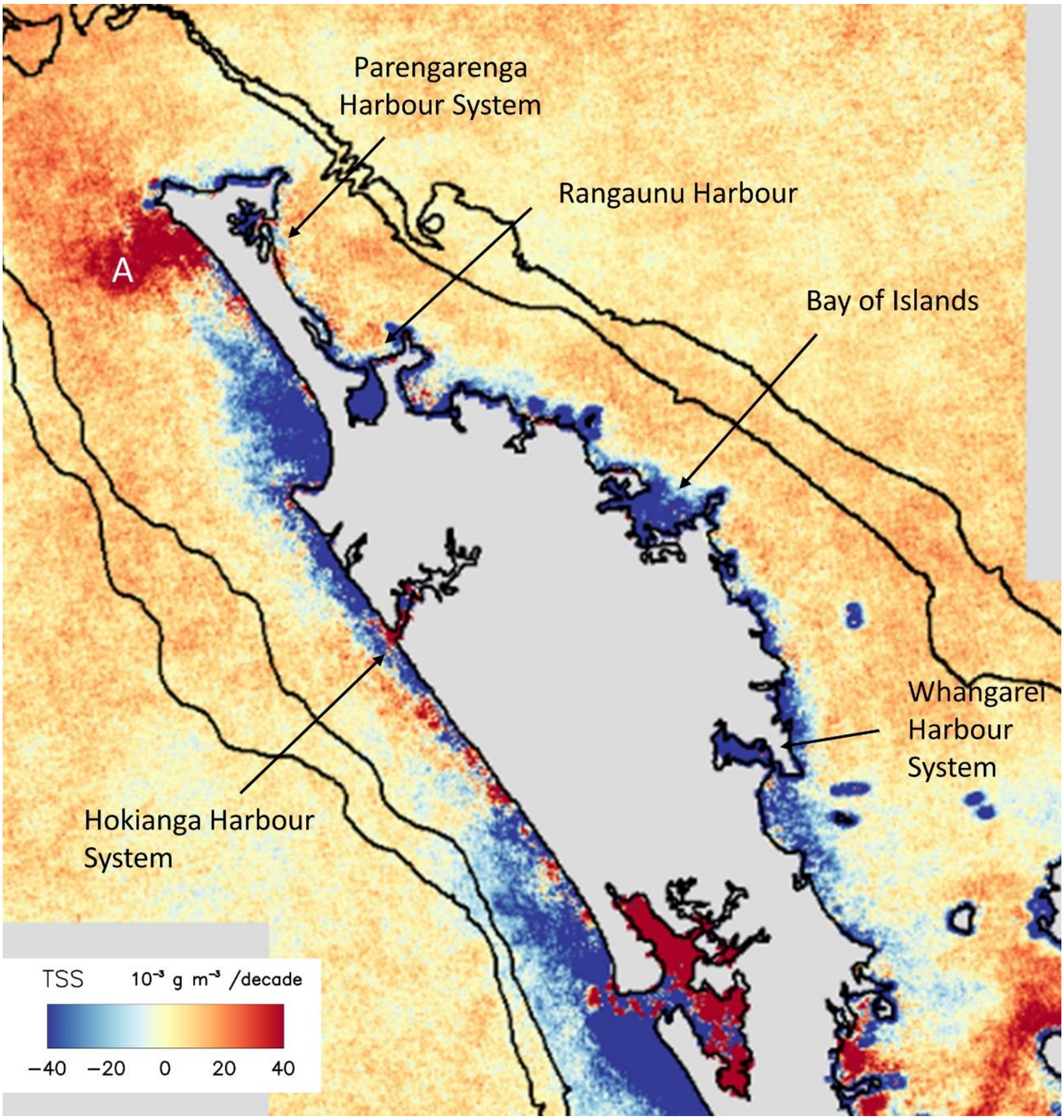

Figure 6-12: Northland: spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. Sen-slope (linear) trends in TSS from deseasonalised monthly satellite estimates are shown as colours (red=increasing trends; blue=decreasing trends). All trends are shown, regardless of statistical significance. No data or no analysis is shown grey. The contours show 250 m and 500 m depth.

6.4.2 Hauraki Gulf/Manukau/Kaipara

There is evidence of increasing TSS in most inner parts of the Kaipara Harbour, but this increasing TSS in the interior of the harbour is not consistently reflected in increasing trends in TSS at its mouth. Patterns of change in TSS in the satellite data are consistent with increasing inflows of suspended sediment and/or nutrients into Kaipara Harbour and increasing deposition rates of sediment within the Harbour.

In the outer Hauraki Gulf, north of Waiheke Island (marked "A", Figure 6-13), there are increasing trends in TSS, which are likely driven by increasing primary productivity. These stretch into the coast on the west of the Hauraki Gulf either side of Whangaparaoa. South of Waiheke Island in most of the Firth of Thames, we see decreasing TSS, consistent with decreasing primary production (i.e. lower growth rates of phytoplankton) or decreasing suspended sediment. There are several small-scale areas of increasing TSS along parts of the southern Hauraki Gulf which are suggestive of increasing input of suspended sediment from land run off: western Firth of Thames (perhaps related to sediment from the Waihou/Piako River), Tamaki Strait, Okura River and Puhoi River.

There is no sign of increasing TSS input in the Waitemata Harbour System or in the Manukau Harbour System. At the broader spatial scale we see decreasing trends in TSS over the last 20 years, likely driven by coastal warming leading to lower primary productivity and hence less phytoplankton-derived particulate material in the water column.

Along the west coast south of Manukau Harbour, the satellite data suggests increasing sediment run off from the Waikato River, but no increase in TSS outflow from the Raglan, Aotea or Kawhia Habour Systems.

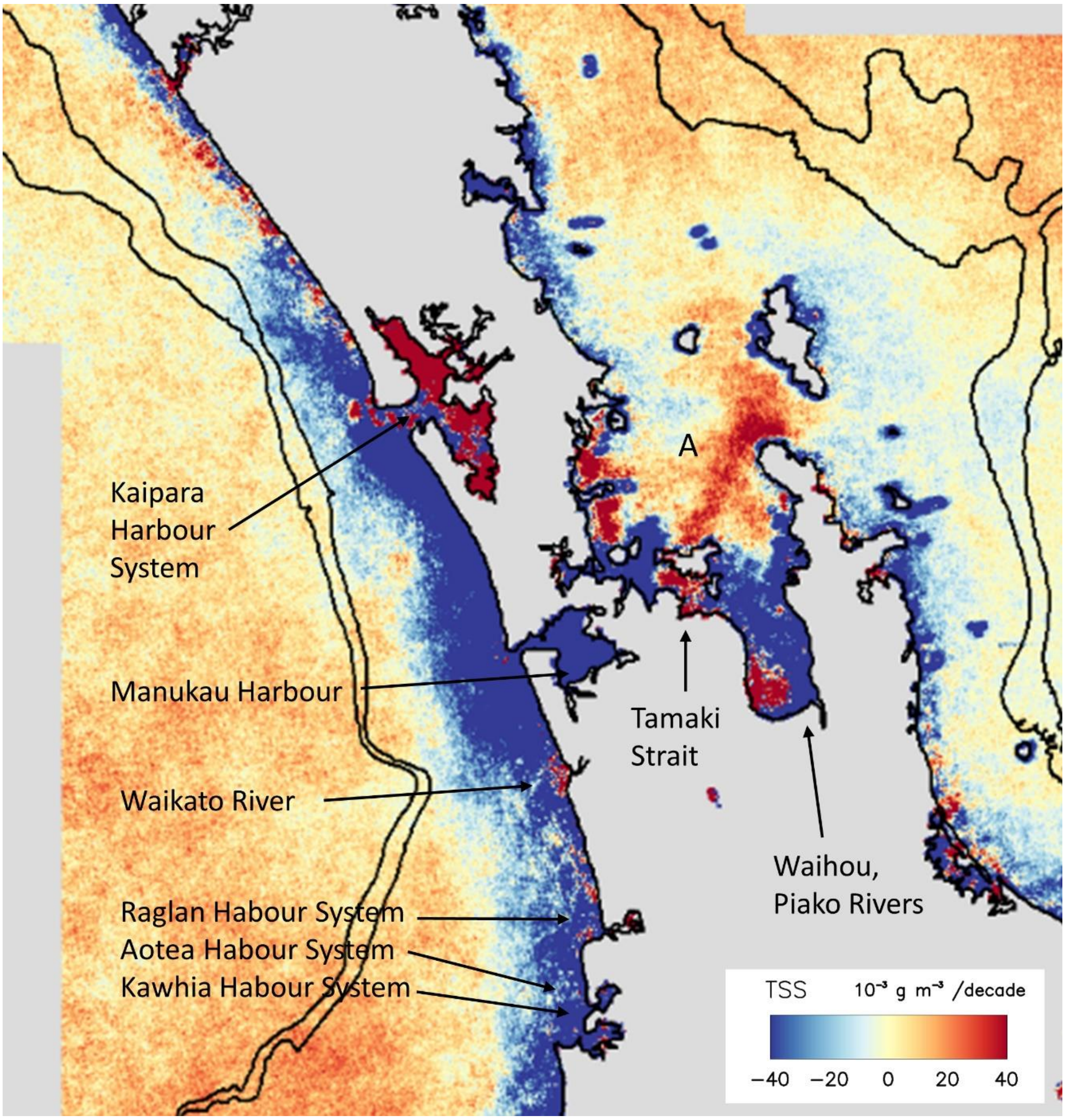

Figure 6-13: Hauraki Gulf/Manukau/Kaipara: Spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. See caption Figure 6-12 for more details.

6.4.3 Bay of Plenty/East Cape/Hawke Bay

The main situation through Bay of Plenty, around East Cape and through Hawke Bay is characterised as decreasing trends in TSS between 2002-2021, consistent with lower primary productivity (less phytoplankton-derived particulate material in the water column) perhaps because of coastal warming (climate effect). Smaller spatial-scale (localised) increases in TSS consistent with increasing suspended sediment and/or increasing primary production are seen close to the outflow of the Tauranga Harbour System (at least in some areas). There is also evidence of increasing TSS associated with the Whakatane River (in Bay of Plenty), and from the Waiapu and Uawa Rivers (eastern East Cape). In Hawke Bay, there is also evidence of increasing TSS (consistent with land-use drivers) from the Mohaka River. There is no clear signal of change in TSS near the mouth of the Ahuriri Estuary or Ngaruroro River.

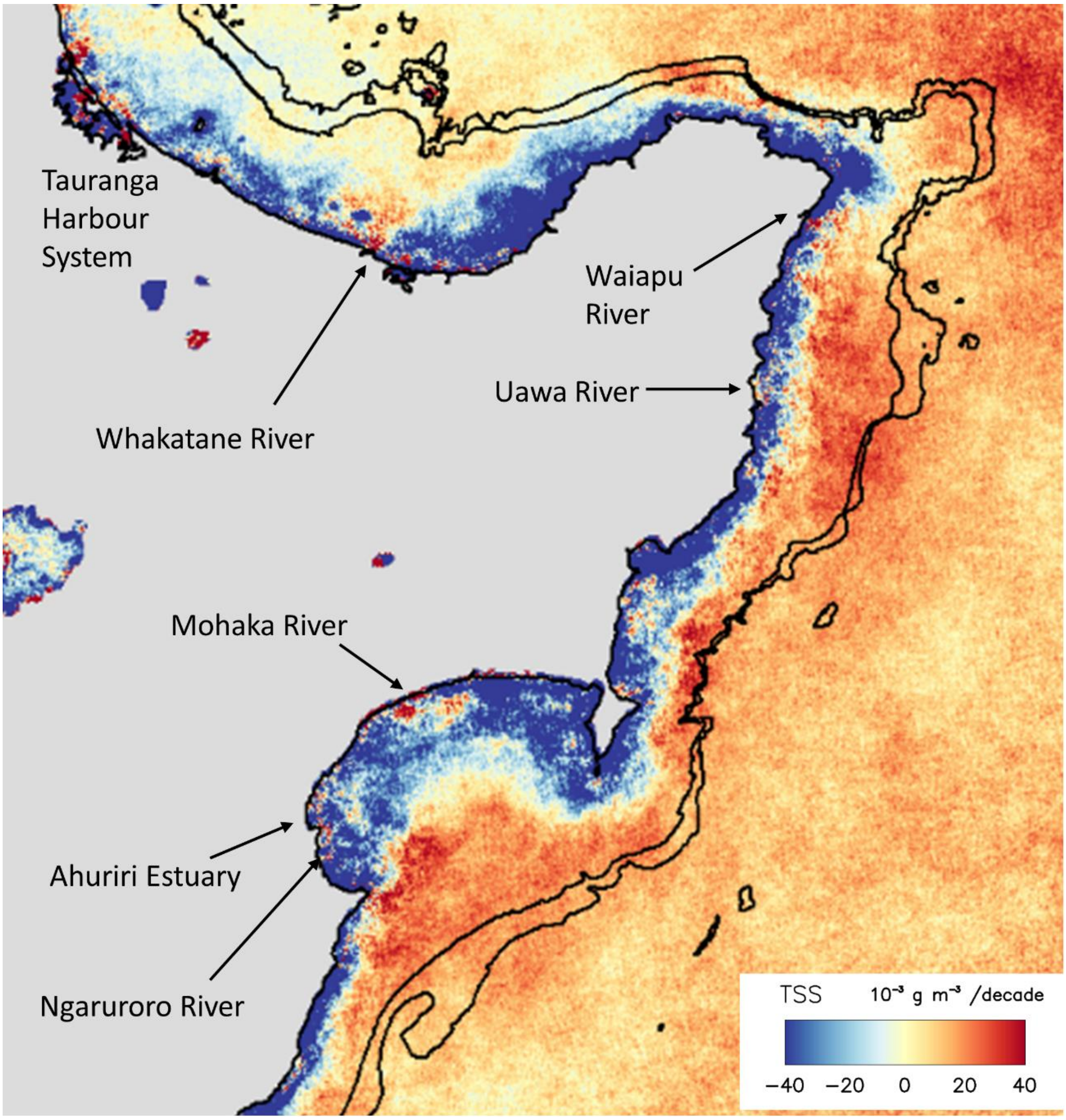

Figure 6-14: Bay of Plenty/East Cape/Hawke Bay: spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. See caption Figure 6-12 for more details.

6.4.4 Wairarapa/South Taranaki Bight/Cook Strait/Marlborough

TSS decreased along most of the coastline of the lower North Island between 2002-2021. This is consistent with large-scale coastal warming leading to lower primary productivity (less phytoplankton-derived particulate material in the water column). There is no evidence of increasing TSS in Wellington Harbour or in any estuaries with three exceptions. Increasing trends in TSS were observed close to the mouths of Kaupokonui Stream and Waingongoro River (northwest of Hawera, but not for Tangahoe River), and Patanui Stream (eastern Wairarapa). These are all relatively minor rivers so changes in TSS may actually be related to changes in resuspension patterns rather than effects of land-use on river-borne material.

Moving to South Island, the satellite data show increasing trends in TSS between 2002-2021 in Golden and Tasman Bays, which contrast with decreasing trends further offshore. The widespread nature of these increases in TSS suggest that increased phytoplankton production is likely the main driver, but there may be an increase in riverine input of particulate material and/or changes to mixing. Increased mixing (for example due to windier conditions) would lead to particulate material staying is suspension longer or benthic sediment being resuspended more often.

Increasing trends in TSS offshore of the Marlborough Sounds and through Cloudy Bay were also observed and did not seem to be associated with land-use changes. Decreasing trends in TSS in the Marlborough Sounds are unreliable because these areas are really too narrow to get reliable satellite estimates of TSS using base data of 500 m spatial resolution. Decreasing trends in TSS west of Farewell Spit are consistent with reduced phytoplankton production (which may be related to reduced upwelling) or lower mixing.

Small-scale increasing trends in TSS are observed at the outflow of the Karamea River and Little Wanganui River which are consistent with changes to the amount of material being brought into the coastal zone by these rivers.

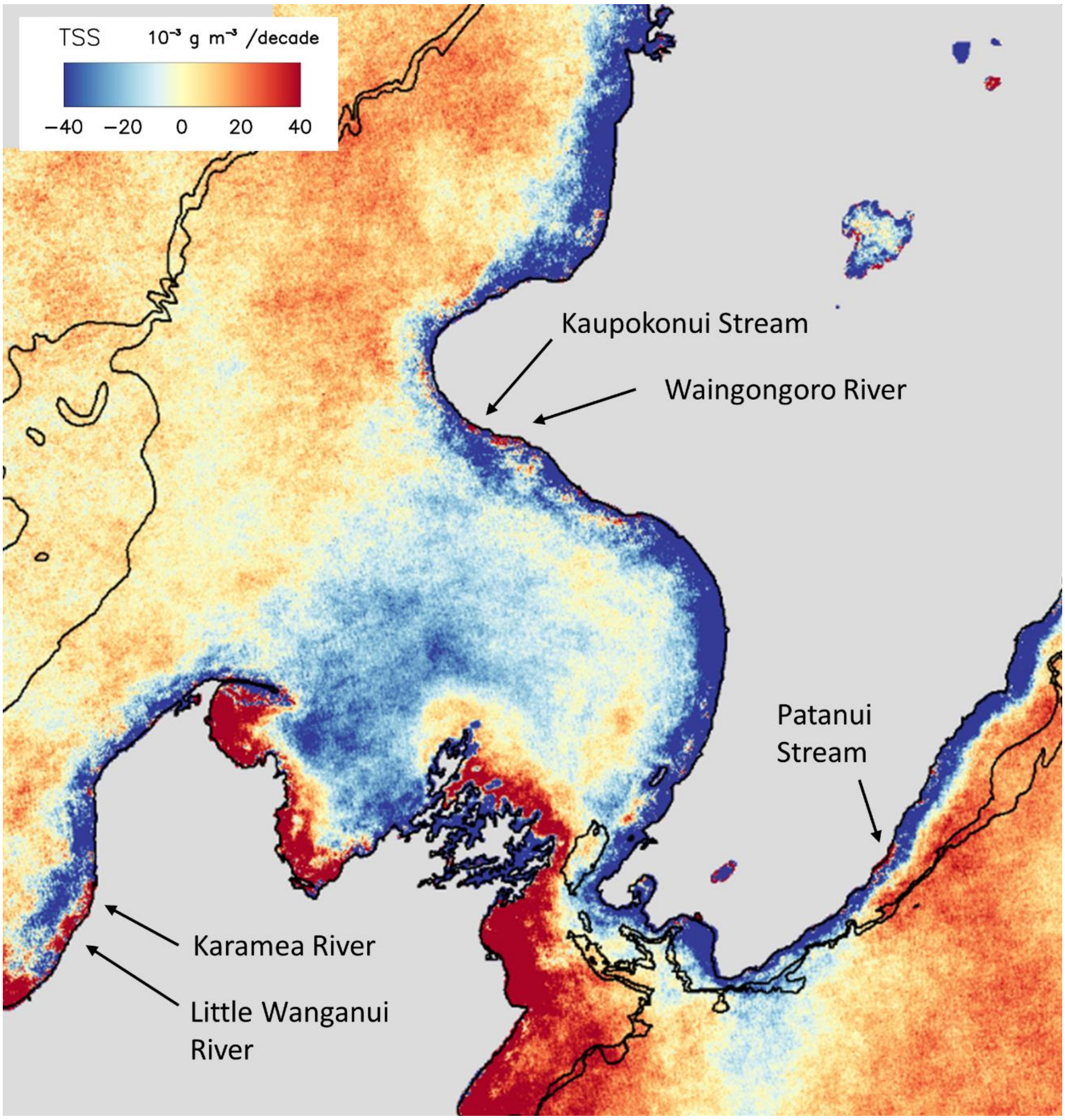

Figure 6-15: Wairarapa/South Taranaki Bight/Cook Strait/Marlborough: Spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. See caption Figure 6-12 for more details.

6.4.5 Canterbury/West Coast

On the west coast of South Island, the satellite data shows generally increasing trends in TSS, with some rather indistinct patches of decreasing trends. These decreasing trends in TSS correspond approximately with the outflows of the Mokihinui River, Grey River, New River, Taramakau River, Waiho River, and Paringa River, and may or may not be related to decadal changes in material (sediment and/or nutrients) carried in the rivers.

The positive trends in TSS along most of the west coast are consistent with large-scale coastal warming leading to increasing phytoplankton productivity and biomass, but also consistent with increasing suspended sediment run off from west coast rivers. For example, there is evidence of increasing trends in TSS close to the terminal reaches of the Hokitika River, Waitaha River, Wanganui

River, Poerua River (Hikimutu Lagoon), Whataroa River, Cook River, Karangarua River, and Haast River but it's not possible to resolve changes near to these rivers separately.

On the east coast of South Island, there is a complex picture of increasing and decreasing trends in TSS in the satellite data. Where the plumes from multiple rivers blend together (e.g. Ashley, Waimakariri and Avon-Heathcote Rivers), separating trends in TSS from each becomes impossible, but sometimes trends at the river mouths are spatially distinct. For instance, there is evidence of increasing TSS offshore of Hirunui River, Waipara River, Rakaia River, Ashburton River, Rangitata River and Waitaki River.

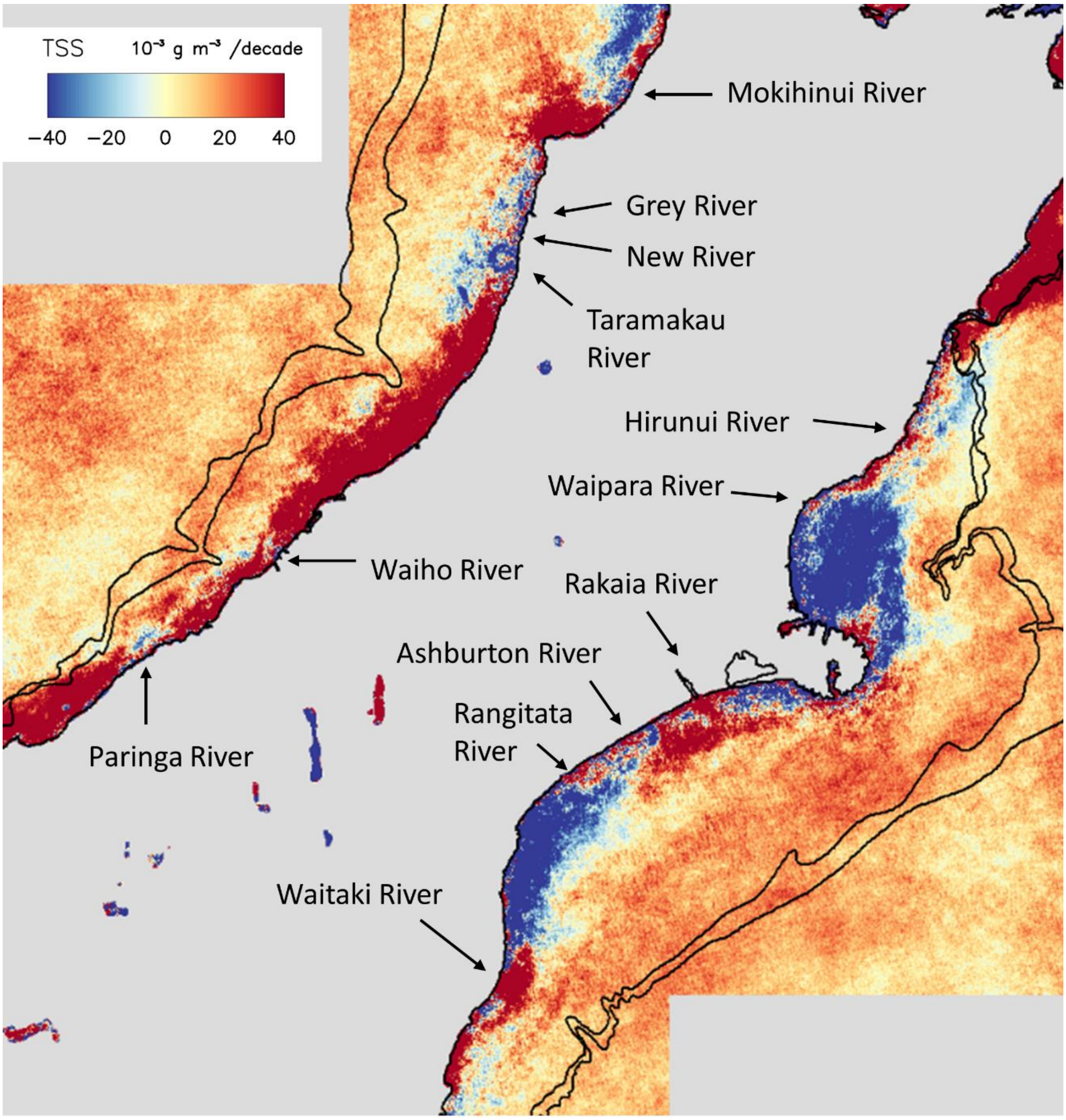

Figure 6-16: Canterbury/West Coast: Spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. See caption Figure 6-12 for more details.

6.4.6 Southland/Stewart Island

Around the south of South Island between 2002-2021, the predominant pattern is increasing trends in TSS is along the west and south coasts, and decreasing trends on the east coast and around Stewart Island. Along the west coast, there is evidence of decreasing trends in TSS around the mouth in some Fiordland Sounds and increases in others so that it is difficult to separate the effects. Set against this pattern are decreasing trends in TSS at the lower reaches and mouths of Dusky Sound and Chalky Inlet. Further east, TSS seems to have increased near the mouth of Waitaki River, Kakanui River, Tokomairiro River, and Clutha River.

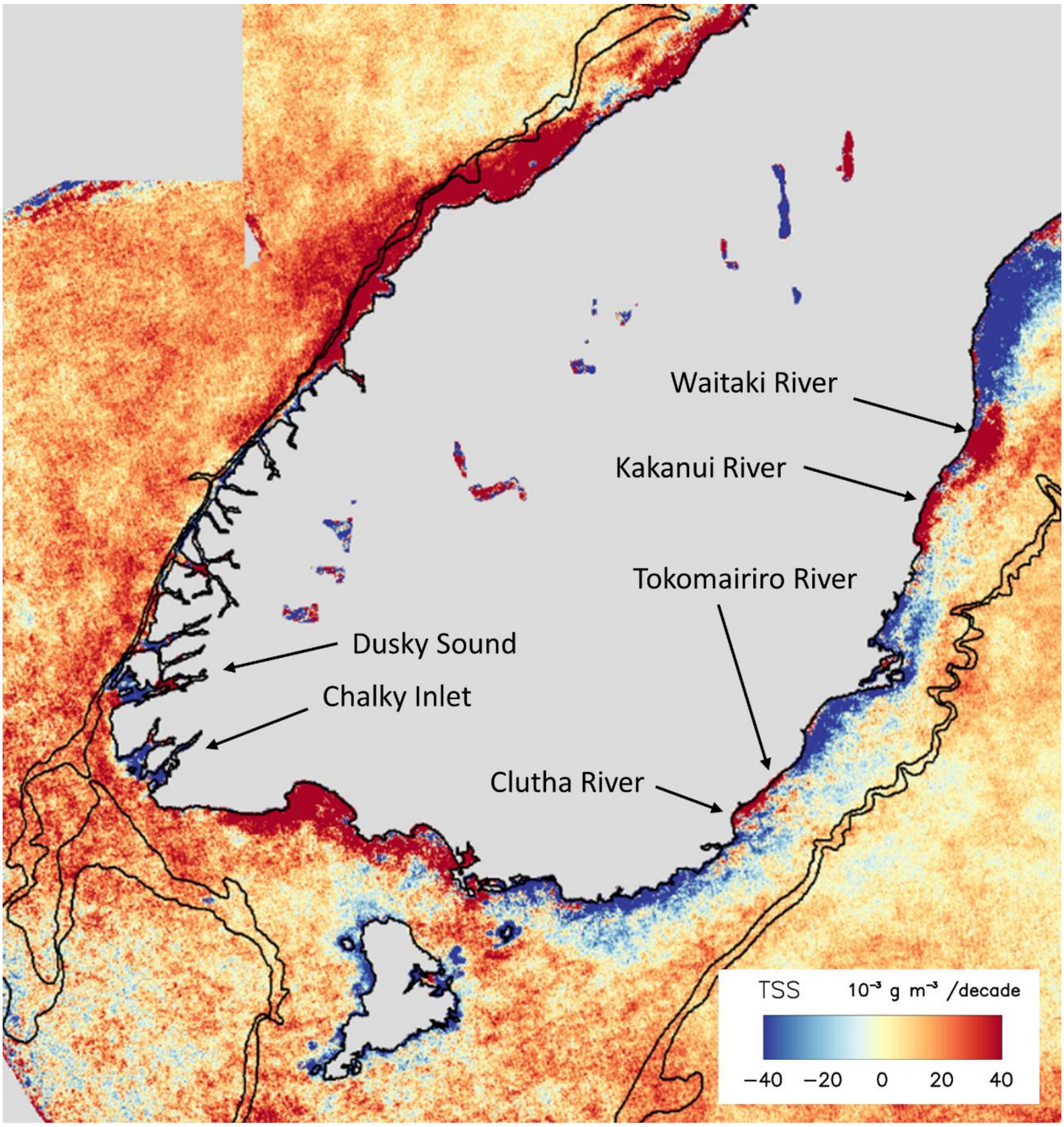

Figure 6-17: Southland/Stewart Island: Spatial trends in monthly anomalies of TSS (total suspended solids) from MODIS-Aqua, 2002-2021. See caption Figure 6-12 for more details.

6.5 Discussion and future work

6.5.1 TSS versus suspended sediment concentration

It is important to note that the satellite data provides an estimate of the total amount of suspended particulate material in the water (including algal and non-algal particulates) at broad space and time scales, but does not necessarily confer information on what this material is, where it has come from, how it will behave or its ecological significance. The satellite TSS product is derived from the estimate of backscatter and hence shows the relative abundance of all particulate material in the water column, including inorganic suspended sediment from land-run off, resuspended benthic material, suspended sediment from coastal erosion, living organic matter produced *in situ*, and detrital organic matter from the breakdown of local primary production. It is not currently possible using the TSS satellite-product alone to separate these different components.

In the future, it may be possible to use combinations of satellite products to tease apart these different factors. For example, the CHL product (which estimates chlorophyll-a concentration in phytoplankton based on satellite-estimates of the absorption of blue light) could be used to try and remove the scattering effects of phytoplankton cells (and maybe even their associated particular organic detritus).

However, developing a more specific measure of the concentration of suspended sediment (i.e. non-algal material) rather than total suspended solids is not straightforward scientifically and no case studies in New Zealand have used this approach to date. The problem is that the absorption-backscatter ratios of phytoplankton vary substantially in time and space as a result of changes to phytoplankton functional type or physiological status, which means that substantial prior knowledge of phytoplankton absorption and scattering properties is needed. In order to gather the required information, a multi-spectral backscatter sensor is now fitted to the NIWA glider system. Continuing to measure this kind of information across New Zealand will help derive a specific “suspended sediment” satellite product in the future.

6.5.2 Drivers of change in TSS

The satellite data show overall patterns of change in all suspended particulate material together. This direct (and rather “blunt”) observation is very different from, say, a model of sediment discharge to the coastal zone from rivers which estimates the effect of a particular process. Hence, research is needed to improve our ability to interpret satellite data for management purposes. Specifically, because TSS includes both algal and non-algal particulates, trends in satellite-observed TSS will depend on both changes in phytoplankton abundance (algal particulates) and on changes in suspended sediment concentration (non-algal particulates). *In situ* measurements show that sediment concentrations and phytoplankton abundance in the coastal zone tend to be positively correlated. There are small-scale and large-scale drivers for this covariance:

- **Small scale**: the same land-use changes that lead to rivers carrying more sediment often also to lead to increased nutrient loads which fertilizes phytoplankton growth. Changes to river flow (e.g. driven by changes to rainfall or water extraction) can also change both suspended sediment and nutrient concentrations (and hence phytoplankton biomass).
- **Large scale**: increased coastal mixing can arise from changes to currents, winds or waves over the continental shelf and can lead to changes in sediment persistence (how

long the sediment stays in suspension), coastal erosion rates and phytoplankton productivity.

As explained above, in due course it should be possible to separate changes in TSS arising from changes to phytoplankton abundance from changes arising from concentrations of suspended sediment because the absorption spectrum of phytoplankton differs markedly from the absorption spectrum of suspended sediment. However, river-borne sediment, material from coastal erosion and resuspended sediment are likely to have very similar optical properties which means they cannot be separated using satellite data. *In situ* and modelling studies, used together with satellite data, offer the best prospect of understanding these different components. It is also possible to use the *spatial patterns* of changes in TSS to help interpret the drivers of the observed changes.

The figures in Section 6.3 and Section 6.4 show the interplay between small-scale changes (less than ~20 km, around the mouth of an estuary) and large-scale changes (>20 km along the coast and out over the shelf). Where there is no bathymetric feature occurring with the change, small-scale trends in TSS around the mouth of an estuary strongly point to this being caused by changes in the terrestrial-input of sediment. For example, from the satellite data we can suggest that some change in the Whakatane River between 2002-2020 has led to an increase in TSS; this is likely to be increased sediment outflow or higher nutrient loads or both.

In contrast, larger scale changes in TSS that occur with corresponding changes in phytoplankton abundance could be due to climatic drivers such as ENSO, or the predominant widespread warming of water over the New Zealand continental shelf. Large-scale changes in TSS not associated with phytoplankton changes could be due to changes in local resuspension of benthic sediment or changes to coastal erosion (e.g. due to shifts in wave or current patterns).

Thus, the spatial patterns in trends of TSS are potentially informative of the dominant driver of environmental change in the coastal zone, making the data potentially very useful for prioritising remedial or management action and in anticipating ecological change. Following on from the preliminary assessment of causes to observed patterns in TSS given in Sections 6.3 and 6.4, we recommend that more formal and objective methods for analysing and reporting spatial patterns in trends of TSS and other satellite products be investigated.

Finally, it is important to note that ocean colour satellites detect changes in the optical backscatter arising from suspended particulate material (i.e. the amount of light scattered by particles in the water) and not the actual concentration of particulate material in the water column. The relationship between particulate backscatter and gravimetric concentration depends on the size spectrum of the particulate material. Hence, there may be long-term trends in particulate backscatter (and hence satellite-derived TSS) but no equivalent trends in gravimetric sediment concentration, and vice versa. For example, a shift to having more small particles could increase backscatter and satellite-derived TSS at the same time as there is a reducing trend in the mass of sediment present. Hence, we have two further recommendations: (1) ongoing *in situ* monitoring of suspended sediment concentration using the laboratory-based gravimetric method in key (prioritized) locations (for example, those locations identified in Section 6.4); and (2) environmental scientists, managers and stakeholders to decide together whether the aim is to manage suspended sediment concentration *per se* or whether managing the optical effect of suspended sediment is preferred (see also Section 2.1).

6.5.3 Relation to MfE Sediment Load Estimator (SSYE)

A New Zealand national GIS 'layer' to enable reconnaissance-scale estimation of suspended-sediment yields from New Zealand's rivers and streams has been developed by NIWA in collaboration with Landcare Research[53]. Predicting long-term average suspended-sediment loads in rivers and streams is useful for dealing with a variety of issues including exploring sediment entrapment rates in potential reservoirs and the vulnerability of estuarine and coastal marine habitats to sediment influxes from the land.

SSYE uses a raster-based GIS layer of specific suspended-sediment yield (SSY, t/km^2/y) from New Zealand's rivers and streams (Figure 2-3) and was generated based on gauged sediment yields at over 200 river stations and an empirical model (Hicks et al., 2003, 2011, 2019). The model relates sediment yield per unit area to mean annual rainfall and to an 'erosion terrain' classification, and has been calibrated off the river-gauging data. The erosion terrains were defined by Landcare Research on the basis of slope, rock type, soils, dominant erosion processes, and expert knowledge. The resulting map of sediment delivery to rivers and streams has been adjusted over the gauged catchments so that the sediment yield predicted by the empirical model matches the gauged yields. The layer can be used to estimate suspended-sediment delivery to rivers and streams from within any defined catchment boundary.

A new publicly available portal will be released in early 2022 which will enable the Suspended Sediment Yield Estimator (SSYE) data to be interactively explored[54].

The SSYE provides information (an estimate) on the mass flow rate of inorganic particulate material (sediment) entering the coastal zone from rivers and streams whereas the satellite data provides direct observations of the optical signature of all suspended particulate solids. Hence, these data will differ due to:

- **Particulate material from terrestrial sources versus local sources**. The satellite sees all particulate material in the water, including that from rivers, resuspended from the seabed, eroded from the nearby coast, and produced *in situ* by biological primary production. The MfE sediment load estimator only estimates sediment yield from rivers.
- **Supply rates differ from standing stock**. The relationship between the supply rate of sediment and standing stock of TSS depends on the loss dynamics, i.e. does the sediment stay in suspension or fall out? These loss dynamics will vary substantially in time (e.g. high deposition rates in calm weather; low deposition rates after storms) and space (depending on waves, depth, currents etc).
- **Vertical distribution of particulate material in the water column**. If the near surface concentration of suspended sediment is not indicative of the depth-averaged concentration (for example, because of significant stratification or high bed-load component), the amount estimated from satellite and amount actual transported (estimated by MfE sediment load estimator) will differ.
- **Variability over time**. The MfE sediment load estimator estimates sediment load based on rainfall and the variation in this with time, whereas the satellite estimates an

[53] 5.1.7 Suspended Sediment Yield Estimator (SSYE): http://tools.envirolink.govt.nz/dsss/suspended-sediment-yield-estimator/
[54] Helen Kettles, pers. com. (Department of Conservation)

average of near-surface sediment at cloud-free times. Near surface sediment concentrations in the coastal zone will decline after a large sediment (rainfall) event so the mismatch will depend on the speed of this settling/particle transformation and the time between the rainfall event and the next clear satellite image.

- **Sediment versus TSS.** As discussed in Section 6.5.1, suspended sediment concentration and TSS differ, depending on particle size distribution and the presence of organic (algal) particulates. Although inorganic sediment will tend to dominate total particulate material concentration, algal material can be more optically active because the particles tend to be smaller.

7 Conclusions and recommendations

7.1 National assessment of long-term trends in coastal sediment

The report presents an analysis of trends in the concentration of Total Suspended Solids (TSS) in the New Zealand coastal zone 2002-2021 from monthly MODIS-Aqua satellite images. Seasonality was removed, but residual effects of climate cycles can still affect these linear trends and within-season trends (e.g. trends in a given month or in a given season such as summer) can be different to the overall (annual-scale) linear trend.

In general, we found *increasing* trends in TSS concentrations (> 3 mg m^{-3} yr^{-1}, about +0.3 %/y) around coastal regions of the South Island, while most of the North Island has *decreasing* trends (< 3 mg m^{-3} yr^{-1}). Broad-scale trends in TSS will result from a combination of changes in phytoplankton-derived particulates (climate- and nutrient-driven variations in primary production), in conjunction with changes in oceanographic conditions which influence coastal erosion and resuspension of benthic sediment (e.g. wave climate), as well as changes to land-run off of suspended sediment.

On finer spatial scales, patterns of long-term change in TSS close to some estuary and river mouths (both increasing and decreasing trends) strongly suggest decadal changes to terrestrial (riverine) input of TSS to the coastal zone are responsible. The locations where changes to TSS over this period are likely related to changes in the riverine supply of suspended sediment are identified in the report in Section 6.4.

In Section 6.5.3 this report considered how satellite-derived TSS estimates (spatial and seasonal patterns) relate to inputs derived from the Ministry for the Environment's 2019 sediment load estimator. In summary, there is not expected to be a clear relationship for a variety of reasons including the fact that the satellite sees all particulate material from both terrestrial sources and local sources (including local erosion and resuspension, and particulates from local primary production) whereas the sediment load estimator only considers sediment yield from rivers. Other differences include temporal mismatches between the approaches (time-averaged versus time-resolved), the effects of vertical distribution of particulate material (satellite data does not see bedload), and variability in the relationship between particulate mass and optical backscatter. Furthermore, the MfE sediment load estimator does not estimate changes to sediment supply over the period of satellite observation. However, it would potentially be possible and instructive to use the MfE sediment load estimator together with changes to landcover (e.g. Landcover Database, LCDB v5.0) over time, and with variations in climate (rainfall) to estimate changes to sediment load annually over the satellite period (20021–2022); see Recommendation 13.

7.2 Observation techniques for coastal sedimentation

An overview of the current state-of-the-art regarding tools and techniques to observe coastal sediment was presented in Section 3 (satellite methods) and Section 4 (radiometric and immersed-instrumentation observations). Summary information on NIWA-SCENZ is given in Appendix A. These sections provide a summary of advantages/strengths as well as caveats/limitations of different observation approaches and highlight future directions and developments. These considerations were used to inform the recommendations given below.

7.3 Case studies

A literature review of how various techniques have been used in Aotearoa New Zealand was given in Section 5. These considerations were used to inform the recommendations given below. The case studies show that *in situ* sampling is needed to locally-tune satellite methods for estimating TSS. There were generally two levels of fieldwork carried out to improve remote sensing for sediment:

1. In some cases, specialised (research) bio-optical equipment was deployed from vessels, including using profiling multichannel radiometers to measure diffuse attenuation, and *in situ* attenuation-absorption meters (AC-9) to measure inherent optical properties. These *in situ* bio-optical methods were combined with specialist laboratory analyses for example to measure chl-specific absorption, backscatter-to-absorption ratio for sediment, the exponents of CDOM and sediment detrital absorption, and the special shape of backscattering. The cost of this kind of field activity is high and requires a high level of investment in specialised equipment and expert personnel. At present, it is not possible to routinely do these specialised bio-optical fieldwork or sample analysis, or do them at very many locations. However, in key focus areas, and to provide the specific information needed to advance the science, this kind of research is appropriate and necessary and should be continued.

2. The second level of fieldwork is more suited to regular sampling by agencies such as DOC and Regional Councils, or organisations required to monitor discharges or conduct environmental impact assessments. To link better with satellite observations, this fieldwork should measure Secchi depth, turbidity, and TSS simultaneously (or on the same water sample) at a number of sites on a regular basis. The case studies show that this can be a useful combination of measurements for validating and locally tuning satellite data for sediment and water clarity. Analysis of chl-a concentration at the same time would also be useful. A crucial element is that the turbidity instrument used must be standardised for this to be useful because different turbidity sensors do not measure the same thing. The NRWQN biogeo-optical data measured turbidity in the laboratory using a HACH 2100AN turbidity meter but this is now obsolete, highlighting the issues of relying on a single design/model of turbidity sensor rather than a true physical standard. We recommend that a specialist group be tasked with recommends the models of turbidity sensors to be used (field and laboratory) and calibration and characterisation methods.

It is clear from the trend analysis and the case studies considered that the spatial resolution of satellite data is limiting applications in small estuaries, harbours, fiords, and small lakes. With the advent of higher-resolution satellite sensors, and the prospect of more of these sensors to provide more frequent overpasses, this is set to improve in the next few years. The next step in New Zealand is to develop pilot studies to see how this new high spatial-resolution data resource performs in relation to coastal sediment in New Zealand.

7.4 Applications of satellite data

DOC is particularly interested in how satellite tools can be used to inform a range of management issues; e.g. threatened species recovery (penguin foraging areas), management for marine protected areas, impacts from large events (landslides, fires) and human activities (dredging, sandmining, coastal development and other land-use changes).

Satellite data gives a measure of patterns and changes to water clarity at the national scale, giving information on both visual clarity and light penetration in the water. Satellites can also measure chl-a (as a proxy for oceanic primary production) and sea surface temperature. Visual clarity (underwater sighting range) affects predators such as fish, marine mammals and aquatic birds which hunt and forage underwater using sight, and the distributions of these predators are also affected by their prey availability that can often be ultimately linked to primary production. For example, in a recent study, Stephenson et al. (2019, 2020) found that modelled cetacean "relative environmental suitability" (RES) were associated with localised environmental conditions including water turbidity, diffuse attenuation and chl-a. This kind of RES modelling approach is also applicable to understanding seabird distribution patterns (e.g., Raymond et al., 2010; Watson et al., 2013) which is starting to be used in New Zealand (Pinkerton, unpublished data). Models of zooplankton abundance (key prey species for many predators) have also been generated using satellite data (e.g. Pinkerton et al., 2020). Long-term changes in these environmental conditions observed from satellites can be used in conjunction with these RES models to investigate the effects of climate change and other drivers on important predators. On-going satellite observation hence offers the prospect of providing an early-warning of changes to the spatial distribution and overall habitat suitability for seabirds and marine mammals around the New Zealand coast.

Satellite data can also help identify patterns of coastal conditions to evaluate representativeness in designing networks of marine protected areas (MPA), including identifying where the environment is changing. Over time, satellite data can track changes in environmental conditions in MPAs as a backdrop to monitoring data in the reserve (Pinkerton, 2021).

Changes in TSS and water clarity in coastal regions can result from many causes, such as major events (earthquakes, landslides), changes in land-use that affect sediment run-off, changes in coastal sediment "trapping" in estuaries, climate drivers that affect wind, waves and coastal currents (through effects on coastal erosion and the resuspension and redistribution of sediment), changes in coastal primary productivity (due to oceanographic change or nutrient run-off), and from activities such as dredging and seabed mining that can cause sediment to be introduced into the upper water column. As discussed in Section 6.5, although the overall effect of these changes can have a signal in the satellite data record, often identifying the key driver(s) of the observed change is much more difficult and will generally require region-specific analysis and *in situ* data. We provide recommendations for how this can be achieved in the next sections.

7.5 Recommendations

Detailed recommendations to improve the value of satellite remote sensing over the next 1–5 years are presented below in five sections and these should be read alongside Green et al. (2021). These recommendations are relevant to DOC, but also to other agencies with interest in coastal sediment such as Regional Councils and MfE, and a range of research providers.

Feedback from three stakeholder engagement workshops were used to guide these conclusions and recommendations. In particular, there was much discussion at the workshops on the difference between TSS (as observed by the satellites) and "sediment" (often taken to mean the supply of sediment to the CMA from rivers and estuaries). Satellite TSS data includes sediment from coastal erosion and sediment resuspended from the seabed, but does not include bedload. The workshops also discussed that sediment supply to the coastal environment is profoundly episodic, for example due to flood events and coastal storms, and that satellite data are poor at capturing these short-term events.

The workshops and case studies show that satellite observation, *in situ* and modelling methods are complementary: satellite data are not the "silver bullet". Instead, a variety of *in situ* monitoring and research is needed to improve knowledge and understanding of suspended sediment in the CMA: satellite data should be used alongside *in situ* sampling (regular water collections, lab analysis), autonomous instrumentation (moorings, gliders, cameras) and modelling. The best insights will be achieved by using multiple methods together, and the recommendations provide more specific guidance about how this can be achieved.

In the specific recommendations below we suggest the level of resources likely to be required. It is difficult to do this in advance, so we use three levels; more specific costings will need to be done when the scope of the research has been more specifically defined. We give resource levels as:

1. *Short*: 1-2 years; Probably costing less than NZ$100,000
2. *Medium*: 2-5 years; Approximately NZ$100,000 to NZ$500,000
3. *Long*: 5+ years; Probably costing more than NZ$500,000

7.5.1 Use satellite data to track and understand change in TSS and coastal water clarity

Satellite remote sensing is globally recognized as a valuable component in monitoring water quality (including sediment) and primary productivity in oceanic and coastal waters. Considerable global resources are committed to maintaining and developing the Earth-observation network, including launching and operating satellite sensors, and ongoing work to develop improved methods for calibration, validation, analysis, visualization and application of the data. New Zealand should make more use of this ostensibly free resource. Specifically, the data can help address the need to design and implement appropriate methods for observing, analysing and reporting observations of suspended sediment concentration and water clarity effects in the CMA.

Recommendations:

1. **Use coastal satellite products for TSS and water clarity in national scale environmental reporting:** This report shows how satellite observations can be used to track change in coastal water quality at the New Zealand national scale. We recommend that DOC support this kind of analysis being used in "State of the Environment" environmental reporting in New Zealand. In "tier 1" environmental indicators, information on *how* things are changing in the environment is valuable even if it is not possible to say exactly *why* those change are occurring (the key drivers). Repeating this trend analysis at approximately 3 years intervals in line with MfE environmental reporting schedule would be appropriate. Work required includes: (i) Review the trend-analysis method used in the present report for statistical best practice (similar to those standards developed for NEMS[55]); (ii) decide which satellite products to report. Products available now include: total suspended solids concentration, TSS; diffuse attenuation, KPAR; seabed light, EBED; Secchi depth, SEC; horizontal (black disk) visibility, HVIS; total detrital absorption, ADET; and euphotic zone depth. (iii) select which satellites to use; (iv) determine the most appropriate time and space scales of analysis; (iv) how results should be reported (significance, colour scales etc). At the present time, for monitoring suspended sediment in the New Zealand coastal zone at national scale, the "sweet-spot" for analysis is TSS product,

[55] National Environment Monitoring Standards

moderate spatial-resolution (500 m), monthly time-resolution and covering the period 2002-present from MODIS-Aqua. [*Short*]

2. **Develop collaborative research to understand drivers of trends.** Satellite data can show how TSS is changing but not what is causing the change. Unpicking what exactly the satellite TSS product and its trends are telling us about sources of sediment and the appropriate management response will require wider research. Observed trends in TSS could be due to *inter alia* modifications in land-use (e.g. deforestation, farming practices, coastal protection) and climate change (e.g. phytoplankton production, rainfall patterns, wave climate). Hence, we recommend that (i) satellite data is used to identify "hotspots" of change in TSS and water clarity (e.g. Table 6-1) to prioritise further studies; (ii) different satellite products should be combined / used together to help unpick the type of particulate material; (iii) objective methods for spatial pattern analysis of satellite data should be developed for insight into the scales of processes operating; (iv) reasons for this change not connected with the riverine input of sediment should be examined. This would include investigating if there is evidence of changes in coastal resuspension over the last 20 years (e.g. due to changes in wave patterns or coastal upwelling patterns), or evidence of changes to coastal erosion (e.g. major coastal developments or events such as earthquakes); (v) explore why there may have been changes to the amount of sediment delivered to the coastal zone in riverine runoff or via estuaries, e.g. rainfall patterns, catchment-sediment properties, and sediment transport/trapping. The work in (v) aligns closely with the modelling behind the MfE Sediment Load Estimator, CLUES[56], Landcover Database[57], and the "Catchments to Estuaries" research programme. [*Long*]

7.5.2 Moderate spatial resolution trend analysis

Moderate-resolution satellite data will likely remain the key resource for monitoring change in the coastal zone in the short-medium term (1-5 years). NIWA-SCENZ is a useful portal which allows stakeholders and users to access satellite information of the New Zealand coastal zone and hence develop ideas for new applications related to coastal environmental management. The following recommendations suggest how the usefulness of moderate-resolution satellite data in SCENZ could be improved.

Recommendations:

3. **Implement linear "trend" layers into NIWA-SCENZ:** The spatial data on linear trends shown in this report (e.g. Figure 6-6) should be provided through NIWA-SCENZ for direct user access. This will allow users to explore the data at its full spatial resolution by zooming in on regions of interest. The trend data should be seasonally disaggregated into monthly-trends (12 layers) and seasonal trends (4) as well as the overall annual trend layer. Proportional trends (i.e. change in TSS as a proportion of the median value at a given point) should be included. [*Short*]

4. **Produce and make available analyses of the statistical significance of trends:** Include new layers in NIWA-SCENZ such as Mann-Kendall significance, power-to-detect-trend

[56] CLUES – Catchment Land Use for Environmental Sustainability model, https://niwa.co.nz/freshwater-and-estuaries/our-services/catchment-modelling/clues-catchment-land-use-for-environmental-sustainability-model
[57] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

statistics, McBride "probability of trend direction" and McBride trend importance classification. These would provide insight into the importance of the trends relative to variability. [*Short*]

5. **Implement product uncertainty / variability layers:** Spatial information on uncertainty and variability in NIWA-SCENZ would help users to appropriately use and report satellite data. [*Short*]

6. **Create a blended multi-sensor product**: Moderate-resolution satellite observations of TSS in New Zealand is currently reliant on a single sensor (MODIS-Aqua) which is already working beyond is design lifetime and could fail at any time. VIIRS and Sentinel-3 data are likely first priorities for future-proofing this capability. Furthermore, blending multiple moderate-resolution sensors and processing will likely improve data quality. [*Short*]

7.5.3 New satellite capabilities and products

Satellite technology and capability are advancing at a rapid pace, especially in the area of high-spatial resolution (metres) remote sensing, which opens up new opportunities for monitoring the New Zealand CMA. There is a concurrent (exponential) rise in the volume of satellite data which presents new data storage and management challenges but fortunately, the development of cloud-based satellite storage and access/analysis tools is keeping pace with this increase in data volume. Together, these changes will necessitate a change in how New Zealand manages and uses satellite data in the next 5 years.

Recommendations:

7. **Co-develop applications of new satellite capability:** Satellite observation is a powerful resource, but is not without issues and limitations. New Zealand should actively seek new applications of satellite data whilst maintaining an awareness of limitations. In doing so, the pros and cons of satellite methods should be understood to ensure the data are used appropriately. A partnership to facilitate engagement between scientists and coastal environmental managers should be formed to work out how to support the development, availability and application of new satellite products for the New Zealand coastal zone. Topics should include co-developing applications, improving data access (using cloud-based and local databases), upskilling/education of users to understand limitations, and preparation of joint research funding applications. [*Medium*]

8. **Generate and assess high-resolution TSS products for New Zealand:** By harmonising across Landsat (4-8) and Sentinel-2 datasets, it should be possible to produce a high spatial-resolution (30 m) TSS product (16 day), delivered via a GEE-app for general use (GEE-SCENZ-30M), relatively quickly (within a year). This application could be compared to existing data and other (moderate-resolution) satellite data and, if deemed useful, could provide insight into water-quality changes across coastal, estuarine and all (small) freshwater bodies back to 1984. [*Medium*]

7.5.4 Improve *in situ* monitoring

Satellite data are best used as part of an integrated observation system, together with *in situ* characterisation and monitoring, and sediment/hydrodynamic modelling. DOC could lead a review of approaches to cameras and *in situ* sampling of coastal water quality involving stakeholders (e.g. regional councils, local authorities, MfE, MPI) towards delivering a nationally-coordinated approach. This should use multiple observing tools, *inter alia*: (i) water collection and laboratory analysis (TSS, chl-a); (ii) *in situ* measurements (Secchi depth, optical backscatter/turbidity); (iii) autonomous marine sensors (gliders, moorings, drifters, seabed light sensors); (iv) fixed, shore/bridge camera stations; (v) river flow and turbidity monitoring. Ways of expanding the funding for this should be sought through co-developed funding applications.

Recommendations:

9. **Improve usefulness of *in situ* measurements**: The value of regular (e.g. monthly) monitoring of sediment concentration (TSS) at coastal sites could be improved by measuring Secchi depth, beam attenuation, and optical backscatter at the same time and same location as taking the water sample. Previous work using *in situ* data to locally tune and validate satellite products has shown that obtaining matching information on attenuation (beam and diffuse), optical backscatter and TSS concentration is valuable. Turbidity can be used as a proxy for optical backscatter but because different turbidity sensors approximate optical backscatter in different ways, co-ordination/standardisation, better calibration and improved characterisation of turbidity sensors used by different agencies is needed. [*Medium*]

10. **Use satellite observations of trends to prioritise more detailed *in situ* studies**. The satellite analysis could be used to identify "hotspots of change" to help guide prioritisation or action on land-use practices in specific catchments/rivers/estuaries. First, the satellite data should be used in a conversation with users, managers and stakeholders to identify which estuaries, rivers or streams seems to show evidence of change in the supply of sediment to the coastal zone over the last 20 years and should be the priorities for study. A preliminary analysis of this information is given in Section 6.4. [*Medium*]

11. **Carry out specialised bio-optical characterisation in priority areas:** More specialized bio-optical fieldwork could also be focussed on these priority areas. This fieldwork should include characterisation of the inherent optical properties of coloured material, specifically: chl-specific absorption, backscatter-to-absorption ratio for sediment, the exponents of CDOM and sediment detrital absorption, the special shape of backscattering, and the backscatter to turbidity relationship. [*Medium*]

12. **Expand monitoring of suspended sediment in rivers and estuaries:** *In situ* monitoring of the supply of suspended sediment to the coast from rivers and estuaries should be expanded and made more consistent. We recommend a review is carried out to produce a national-scale plan for better *in situ* observation of riverine suspended sediment, taking into account synergies with satellite capability. Leverage the flow gauging telemetry network and include turbidity sensors as part of the monitoring by National River Water Quality Network (NRWQN – NIWA), regional councils and local authorities. Continuous monitoring across flood hydrographs and basal flows could provide information on sediment input into estuaries and coastal river plumes that are missing in satellite data. The TSS trend analysis presented here can help prioritise monitoring. [*Long*]

13. **Support the development of new *in situ* monitoring technology**. Autonomous monitoring is likely to become the most appropriate way to monitor and understand coastal sediment. We recommend DOC support the development and commit to being early adopters of this new technology. For example: (i) low-cost autonomous seacraft for the coastal zone with a particular focus on water quality (suspended sediment concentrations) and shallow benthic habitat mapping (where are the sediment-sensitive habitats on a national scale?) (ii) multispectral cameras for mapping suspended sediment from helicopters or small-planes, including calibration and data processing methods; (iii) self-contained radiometric sensors (perhaps with solar panels and cellphone data connection) that could be mounted from high shoreline vantage points and/or bridges to provide near-continuous monitoring (during daylight) information on TSS; (iv) investigate artificial intelligence forecasting techniques for suspended sediment. [*Long*]

7.5.5 Co-analyse satellite data with other datasets and models

Overall, Earth-observation satellites are a powerful, cost-effective but under-utilized tool for providing information on sediment in the New Zealand CMA. However, they can be somewhat "blunt", providing data on all suspended particulate material present and not on the types of material, sources, transport/deposition processes or ecological effects. To understand the causes of observed change and improve the usefulness of the data for managing coastal sediment, satellite data should be combined with *in situ* and modelling studies, as below.

Recommendations:

14. **Develop a time-varying sediment load estimator**: The present MfE sediment load estimator does not estimate changes to sediment supply over the period of satellite observation (2002–2022). It would potentially be possible to use the MfE sediment load estimator together with changes to landcover over time, and with variations in climate (rainfall) to estimate changes to sediment load annually over the satellite period. Models could be aligned with data in the Landcover Database, LCDB v5.0: summer 1996/97, summer 2001/02, summer 2008/09, summer 2012/13, and summer 2018/19. This would test whether patterns in TSS observed in the satellite data correspond to modelled changes in sediment supply to the coastal zone. [*Medium*]

15. **Co-analyse satellite data with hydrodynamic sediment transport models:** New Zealand should consider developing a national-scale model of coastal sediment transport which includes catchment processes, sediment transport to estuaries, continental shelf scale hydrodynamic model processes, sediment transport, deposition, and resuspension. Satellite and other observational monitoring data on suspended sediment should be used for validation. Methods for assimilating satellite data into the model should be considered. [*Long*]

16. **Analyse satellite data in relation to other existing datasets:** It would likely be useful to overlay the satellite-derived maps of average concentrations and trends in coloured material (especially TSS, CHL and EBED) from Section 6 with spatial information representing factors connected with coastal habitat or ecosystem type, value or vulnerability. Many of these spatial layers are already loaded and present in NIWA-SCENZ where they can be overlaid relatively easily. For example:

- coastal habitat types or bioregions (e.g. coastal-BOMEC; Key Ecological Areas, Stephenson et al. 2018)
- River Environment Classification (REC) scheme terminal reach metrics
- New Zealand River Hydrology (Collins 2020)
- sediment deposition tool[58]
- National Mud Benthic Health Model (BHM) which was developed to detect sediment effects on estuarine benthic communities (Clark et al. 2020)
- wave exposure maps (NIWA, Richard Gorman, pers. com.)
- coastal value estimates (e.g. Beaumont et al., 2010, 2021) following the method outlined in Fredston-Hermann et al. (2016) to prioritise regions for action
- coastal MPAs established and planned
- seabird nesting areas
- protected species occurrence maps (especially for cetaceans, e.g. Stephenson et al. 2019, 2020; Finucci et al.2021)
- substrate type e.g. rocky reefs
- coastal fisheries (catches, effort and fishing gear type)
- marine heat waves (Smale et al., 2019; Thoral et al., submitted)
- dated sediment cores could be useful to provide a time-series of sedimentation for comparison with satellite TSS time series.

[*Medium*]

7.5.6 Summary recommendations

Based on the 16 detailed recommendations given above, here we give three "top" summary recommendations.

Co-ordinate and improve *in situ* TSS monitoring: We recommend improving methods to connect *in situ* monitoring to remote sensing data. The usefulness of regular (e.g., monthly) monitoring of sediment (TSS) at coastal sites would be improved by measuring attenuation and optical backscatter at the same time and same location as taking the water sample. Secchi depth and beam transmissometers should be used to measure attenuation at monitoring sites. Turbidity can be used as a proxy for optical backscatter but because different turbidity sensors approximate optical backscatter in different ways, co-ordination/standardization, better calibration and improved characterisation of turbidity sensors used by different agencies is needed. [Recommendation 9]

Develop pilot studies of new satellite capability: Satellite data relevant to coastal sediment are available at moderate resolution (100s of metres) and go back to 2002 (NIWA-SCENZ). More recently, high-spatial resolution (1–10s of metres) satellite data are available and provide information on

[58] https://niwa.co.nz/freshwater/management-tools/sediment-tools/catchment-to-estuary-sediment-deposition-tool

sediment in smaller estuaries, harbours, fiords, and lakes. Both resolutions of satellite data are currently under-used in New Zealand. We recommend that the national-scale TSS trend analysis presented here be used to select priority areas for pilot studies to explore the utility of the new satellite capability for monitoring coastal sediment. This includes continued development of NIWA-SCENZ. A "sceptical early-adopter" mindset is recommended: scientists and managers should actively seek new applications of these satellite data whilst developing an awareness of limitations. [Recommendations 3-5, 7, 8, 10]

Improve *in situ* monitoring of sediment in rivers and estuaries: Radiometric sensors ("camera like" instruments sensors that measure the colour of water) can provide estimates of TSS concentration using methods similar to those used in satellite processing. These could be mounted from high vantage points and/or bridges to provide near-continuous (during daylight) information on TSS in rivers and estuaries. We recommend exploring whether this radiometric approach could deliver a cost-effective way of monitoring the input of suspended sediment to the CMA. These radiometric sensors could potentially be used in conjunction with continuous *in situ* monitoring (e.g., turbidity sensors in rivers or on moorings). [Recommendations 12, 13]

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9 Glossary of abbreviations and terms

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (NASA)
ASV	Autonomous surface vehicles
AUV	Autonomous underwater vehicles
CDOM	Coloured dissolved organic matter
Chlorophyll-a / chl-a/ CHL	The ubiquitous pigment in marine phytoplankton.
CMA	Coastal management area
coastal mixing	The rate at which water with different properties or constituents is homogenised by turbulence and overturning (due to currents, tides and waves)
CTD	Conductivity-temperature-depth instrument
CZCS	Coastal Zone Color Scanner (the first ocean colour satellite sensor)
EBED	Incident irradiance at the seabed
EEZ	Exclusive Economic Zone.
ESA	European Space Agency
GEE	Google Earth Engine
KPAR	Diffuse attenuation coefficient (m^{-1})
MERIS	Medium Resolution Imaging Spectro-radiometer (ESA)
MODIS	Moderate Resolution Imaging Spectro-radiometer (NASA). There are two MODIS sensors, Terra and Aqua.
Monthly anomaly	How different one month is from the average (e.g. the difference between January 2000 and an average January).
NASA	National Aeronautics and Space Administration (USA)
NIWA-SCENZ	NIWA Seas Coasts Estuaries New Zealand
NOAA	National Oceanic and Atmospheric Administration (USA)
PAR	Photosynthetically available radiation (wavelengths of 400 – 700 nm)
PSD	Particle size distribution (the relative numbers of particles of different sizes)
psu	Practical salinity units
ROFI	Regions of Freshwater Influence
RMA	Resource Management Act
SCENZ	Seas, Coastal, Estuaries New Zealand
SeaWiFS	Sea-viewing Wide Field-of-view Sensor (OrbImage/NASA)

SSC	Suspended sediment concentration (g m^{-3})
SSL	Suspended sediment load (g m^{-3})
SST	Sea-surface temperature (°C)
TSS	Total suspended solids (g m^{-3})
UAV	Unmanned aerial vehicles (“drones”)
USV	Unmanned surface vehicles
VIIRS	Visible Infrared Imaging Radiometer Suite (NASA/NOAA)
WV-2	WorldView-2 (ESA)

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Appendix A SCENZ: Seas, Coasts, Estuaries New Zealand

Rationale

Although substantial satellite data exists for the New Zealand coastal zone, accessing this has traditionally been difficult for a number of reasons: the data volume is high (hundreds of files, data volumes of many Gb); the data have complex file formats; the data are complex, covering a range of timesteps and products (TSS, water clarity, backscatter etc). Consequently, a web-based portal (SCENZ) was created which allows Regional Councils and other scientists and stakeholders to access more than 18 years of satellite observations of water-quality around the New Zealand coastline.

SCENZ focusses on moderate-resolution (500 m) data from MODIS-Aqua.

SCENZ design and structure

A schematic of the system (Figure A-1) highlights the five key parts: (1) data store containing (at present) 25,909 files, with a total volume of 0.67 Tb[59]. Maps are managed in a space and time imagery service dataset (data-cube); (2) visualisation tools for exploring the data; (3) extract tool, to obtain time-series for user-defined regions; (4) analysis tools enabling spatio-temporal analyses; (5) links to external satellite resources.

SCENZ is a complex online system that is at the cutting-edge of satellite data access and analysis. NIWA-SCENZ enables Regional Councils to access to 10 water-quality and coastal satellite products at monthly resolution from July 2002 to November 2020: sea-surface temperature(SST), chlorophyll (CHL), horizontal visibility (HVIS), Secchi depth (SEC), diffuse attenuation (KPAR), total suspended sediment (TSS), particulate backscatter (BBP), detrital absorption (ADET), light at the seabed (EBED), and POB (proportion observed). Each product can be extracted at 4 temporal resolutions: weekly, monthly, seasonal (3-monthly), and annual. At present, visualisation and analysis works only on the recommended resolution (monthly) but will be enabled on the other 3 time resolutions in the future. For each product, three types of data are available: timeseries, climatologies and anomalies, the latter being particularly useful for identifying long-term change in the coastal environment. Extracted data (in csv[60] format) are made available for saving locally (for user-specific investigations) or further analysis online using the NIWA-SCENZ "Analyse" tools. Some example screen-shots are given Figure A-2.

Crucially, NIWA-SCENZ separates the visualisation/extraction (Arc-GIS[61]) and the analysis (R-shiny) components. The use of ArcEnterprise for data storage and management obtains speed and power from a fast-evolving and powerful international, commercial software system; the use of the R-Shiny open-access system means that tools can be modified to respond quickly and flexibly to user needs. We are not aware of any other similar systems that combine the advantages of each approach as NIWA-SCENZ does.

The system is documented online and there is no printed manual. Please see the "Details" tab the following link: NIWA-SCENZ (PROD)[62]

[59] Terrabytes
[60] Comma-separate variable (Ascii text) format.
[61] Geographic Information Systems
[62] https://gis.niwa.co.nz/portal/apps/experiencebuilder/template/?id=9794f29cd417493894df99d422c30ec2

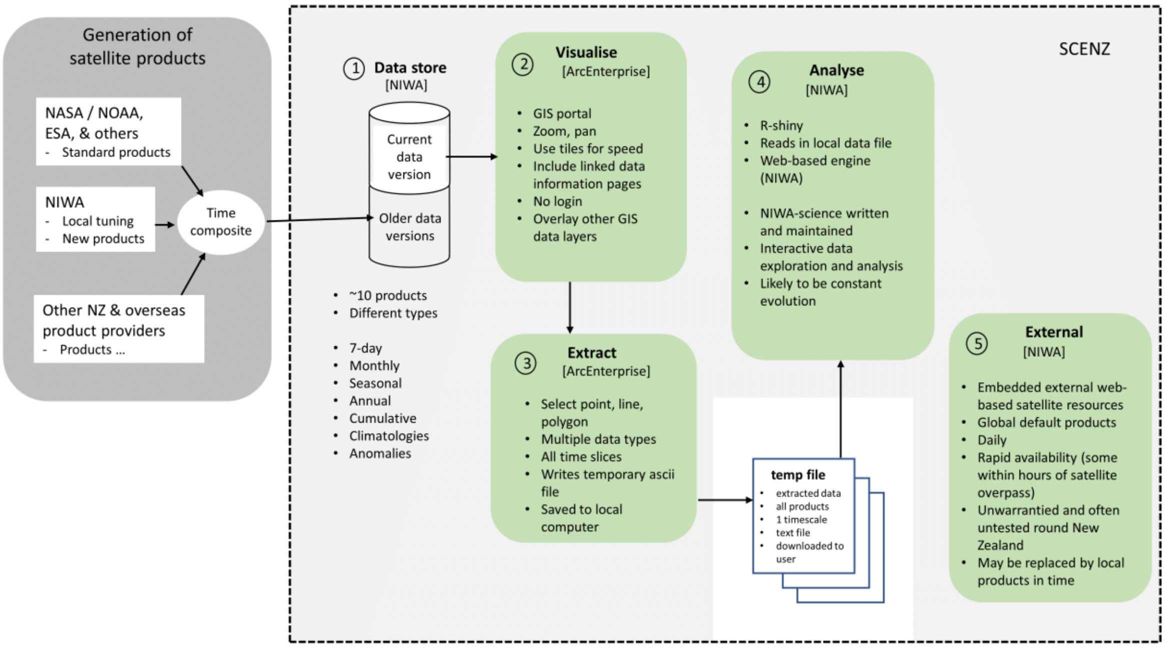

Figure A-1: Schematic of NIWA-SCENZ.

Exploring, visualising and extracting satellite data

Some screenshots of NIWA-SCENZ are shown in Figure A-3: (A) true-colour daily imagery; (B) time-series landing page; (C) timeseries visualisation; (D) anomaly visualisation; (E) area thumbnails.

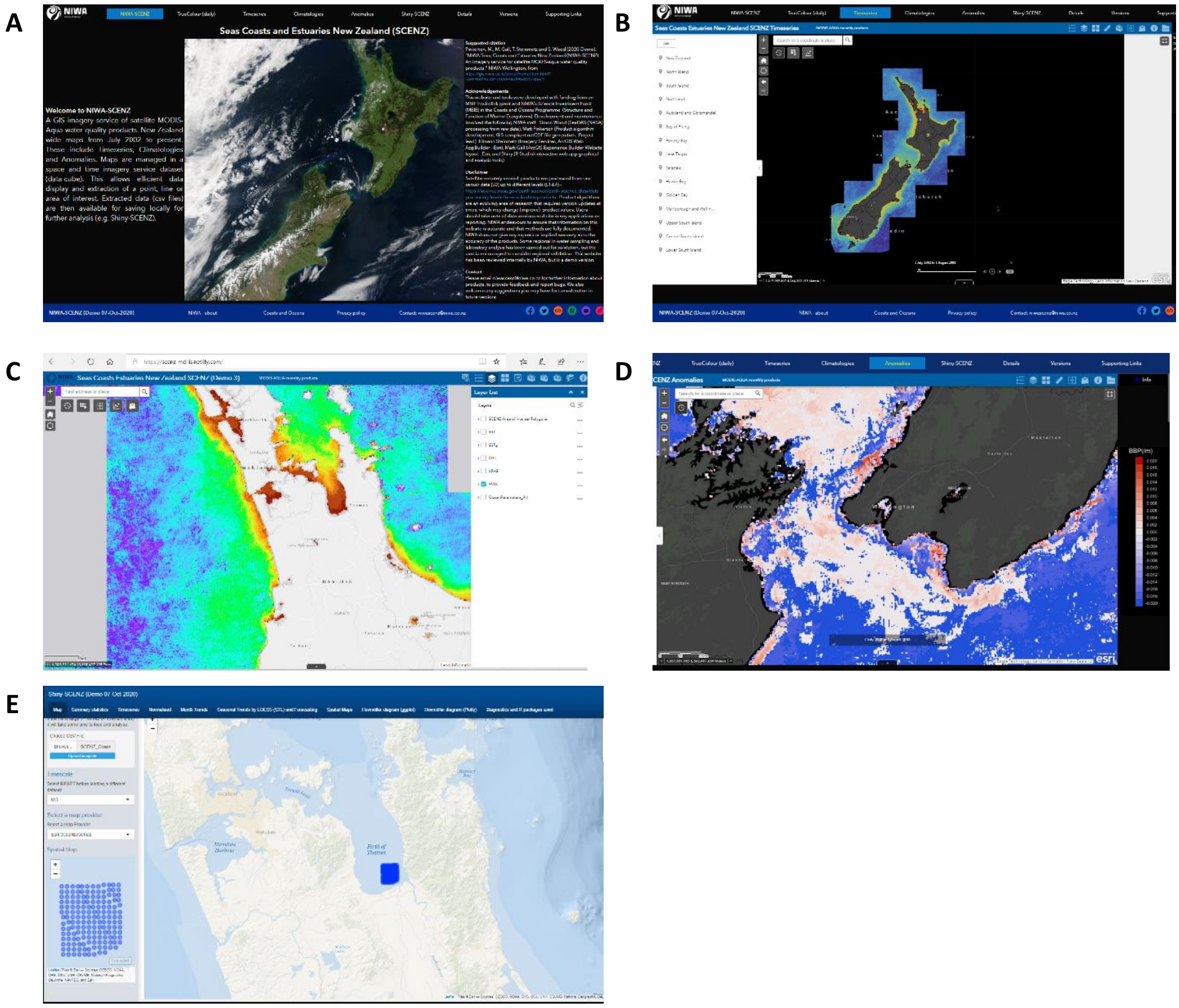

Figure A-2: Screenshots of NIWA-SCENZ. (A) true-colour daily imagery; (B) time-series landing page; (C) timeseries visualisation; (D) anomaly visualisation; (E) area thumbnails.

Analysis tools

Some capability of Shiny-SCENZ is shown below: Figure A-3 (time-series visualisation); Figure A-4 (within-month trends); Figure A-5 (long-term or deseasonalised trends).

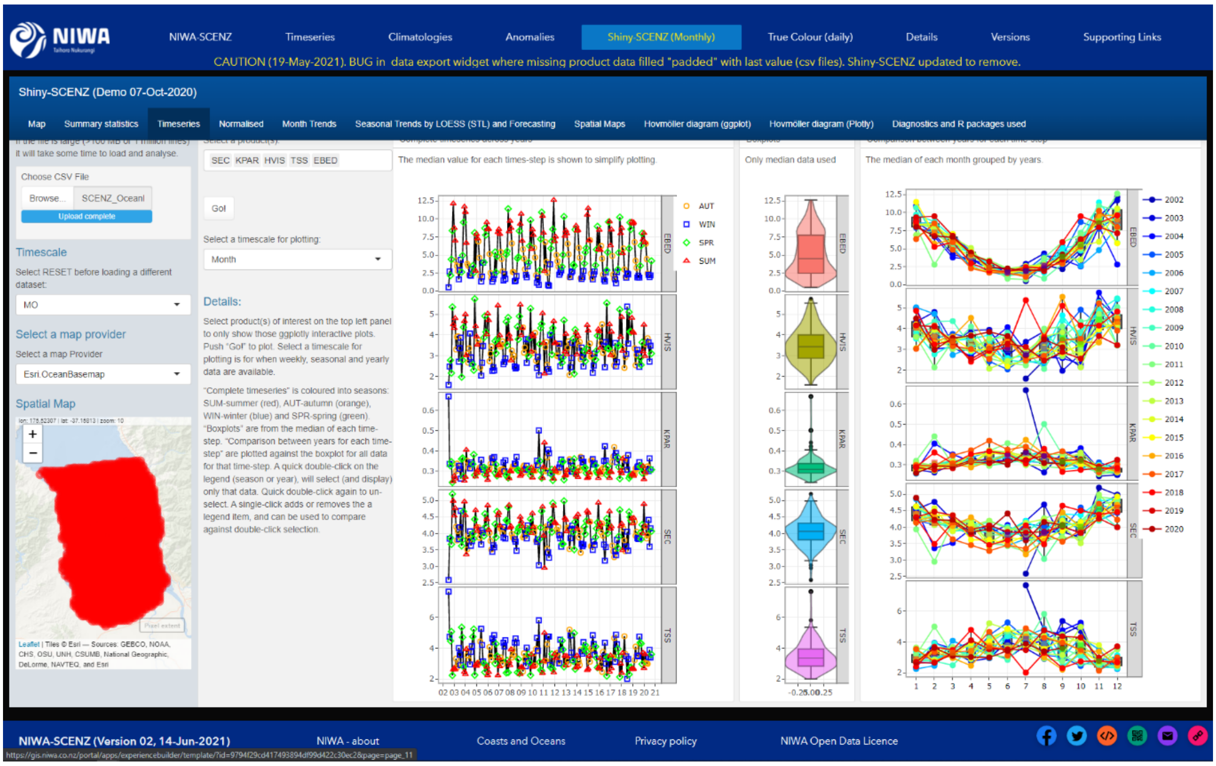

Figure A-3: Shiny-SCENZ, timeseries (EBED, HVIS, KPAR, SEC and TSS) plots for the Firth of Thames region. Select product(s) of interest on the top left panel to only show those ggplotly interactive plots. Push "Go!" to plot. Select a timescale for plotting is for when weekly, seasonal, and yearly data are available. "Complete timeseries" is coloured into seasons: SUM-summer (red), AUT-autumn (orange), WIN-winter (blue) and SPR-spring (green). "Boxplots" are from the median of each time-step. "Comparison between years for each time-step" are plotted against the boxplot for all data for that time-step. A quick double-click on the legend (season or year), will select (and display) only that data. Quick double-click again to un-select. A single-click adds or removes a legend item and can be used to compare against double-click selection.

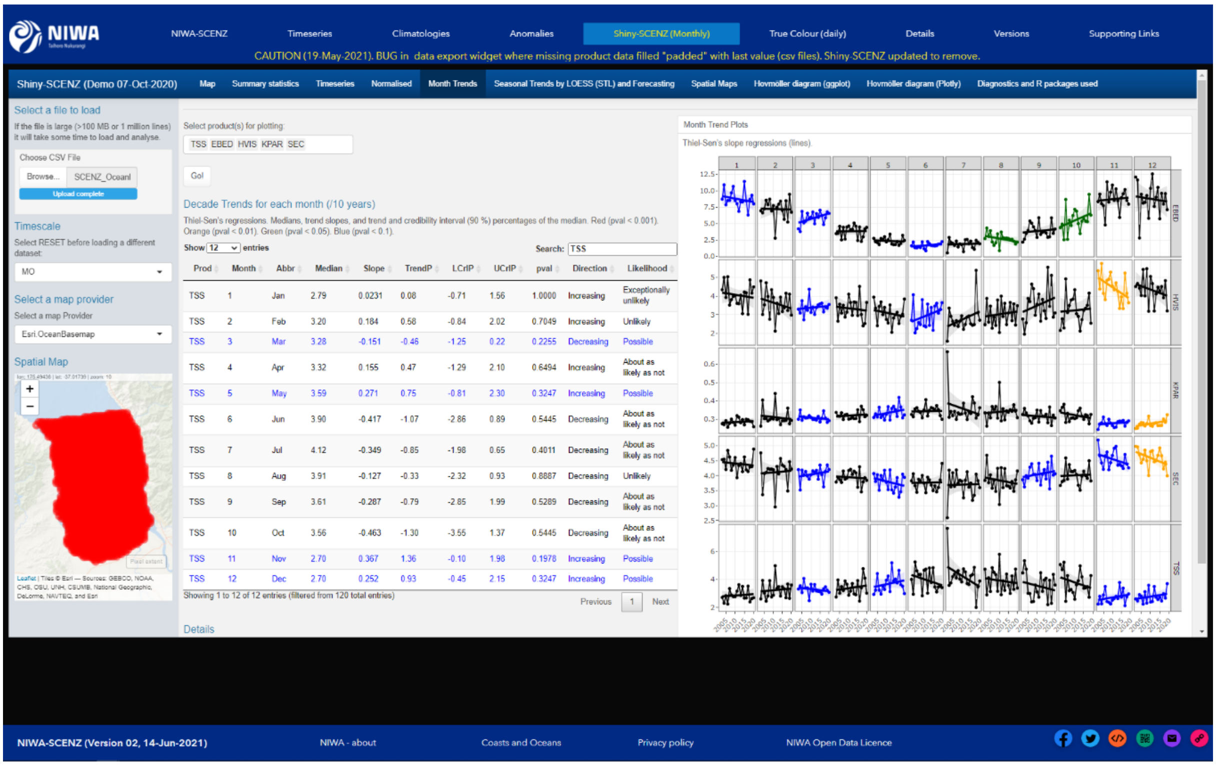

Figure A-4: Shiny-SCENZ Month Trends. Theil-Sen's month regressions and plots for products (EBED, HVIS, KPAR, SEC and TSS) for the Firth of Thames region. Thiel-Sen's regression slopes and statistics - the median of all slopes between all point pairs. Less skewed by extremes compared to ordinary least squares regressions. Further details. Month trends for all products are calculated on decade scales (/10 years). Trend percentages (TrendP), and lower and upper credibility intervals percentages (LCrIP & UCrIP) provide a degree of normalisation of product changes. To calculate an absolute magnitude and range, multiply these by the median value of the product month. The data-table can be sorted by column, filtered (search) and extended to show all entries. Select, copy and paste the table contents to other documents as needed (e.g. Word. Excel). TimeTrends software (Jowett Consulting) provides more detailed procedures should further analysis be required.

Figure A-5: Shiny-SCENZ Seasonal Trends by LOESS (STL) and Forecasting. Seasonal Trends by LOESS (STL - LOcally regrESSion). Used to decompose rawdata timeseries to determine seasonality and trend timeseries, and predict a 36 month forecast. Further details. Both the span of the seasonal window (years), and trend window (months) determine the degree of variability in seasonal, trend and remainder timeseries. Changing the trend window to 1 forces the remainder to be zero and simulates a deseasonalised TimeTrends analysis (seasonal Mann_Kendall trend assessment). The recommended default trend window (1.5*12/(1-1.5/swindow) of 21 should not be used for table statistics as these are not valid, smoothing the trend and biasing significance statistics. Thiel-Sen's slope regressions are calculated on the deseasonalised STL trends. Decadal slopes are also represented as a trend percentage of the median over a decade with lower and upper credibility intervals. The user is encouraged to compare with deseasonalised TimeTrends software (Jowett Consulting).

Appendix B Stakeholder engagement

Engagement in this project has followed the contract. In general, there was good engagement from the users in the project, with workshops well attended and a range of organisations represented including: Alice Bradley (MFE), Alison Grayston (MFE), Andrew Baxter (DOC), Carl Howarth (MfE), Coral Grant (AC), Hannah Jones (WRC), Hendrik Schultz (DOC), Ian Tuck (MPI), Jackson Efford (BOPRC), James Rolinson (MfE), Janine Kamke (WRC), Jean Davis (MPI), Jodie Robertson (DOC), Josh Van Lier (MPI), Karen Tunley (MPI), Lauren Long (MfE), Mary Livingston (MPI), Megan Carbines (AC), Megan Oliver (DOC), Nicole Hancock (DOC), Oli Wade (MRC), Pierre Tellier (MfE), Rebecca Martel (MfE), Rowan Taylor (MfE), Stacey Faire (BOPRC), Stephen Fragaszy (MfE), Stephen Hunt (WRC), Sue Clearwater (DOC), Theodore Kpodonu (AC), Pim De Monchy (BOPRC), Dave West (DOC) Tarn Drylie (AC).

- Workshop 1 was held on 26 July 2021, by Teams and from NIWA Greta Point.
- Workshop 2 was held on 19 September 2021, by Teams and from NIWA Greta Point, using the “padlet” app.
- Workshop 3 was held on Tuesday 7 December 2021, by Teams and from NIWA Greta Point, using the “padlet” app. This focussed on draft recommendations which were reworked following helpful comments from participants.