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Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Investigations and Monitoring Group

Remote sensing of suspended solids in Lyttelton Harbour/ Whakaraupō water using satellite images

Report No. R14/55

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Cover: MODIS-Aqua pseudo-true colour image of Lyttelton Harbour, 2002 day 296.

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Executive summary

Environment Canterbury seeks to use satellite images of ocean colour to assess the spatial and temporal patterns in total suspended solids (TSS) in waters of Lyttelton Harbour / Whakaraupō and Port Levy / Koukourarata. Coastal waters exhibit high natural variability in their characteristic properties, both spatially and temporally. Observations of the ocean from optical sensors on satellites can complement measurements of water properties from boats and moorings ('water-truthing') to provide synoptic distributions of these properties over large areas, at daily and longer timescales.

The variable optical properties of sediment in turbid coastal waters also present severe challenges to obtaining quantitative data from satellite observations. In such regions, local (regional) validation and tuning of processing methods are needed. *In situ* measurements from Environment Canterbury were augmented with data from a NIWA research project based on the National River Water Quality Network in order to develop methods to convert images of ocean colour to maps of TSS in Lyttelton Harbour. The algorithms developed in this study were non-linear and specific to the Lyttelton Harbour region. Satellite-derived TSS predictions were generated at a 250 m spatial resolution and mapped onto a grid encompassing the Lyttelton Harbour / Pegasus Bay region. Images from MODIS-Aqua between July 2002 and April 2014 were used.

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. Ocean colour satellite observations of TSS are complementary to *in situ* observations (from vessels and moorings) by providing a spatial context to field sampling. Satellite images are likely to be a useful part of an integrated approach to monitoring coastal waters.

The main findings from the analysis of the satellite data were:

1. 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 had TSS similar to those at the mouth of Lyttelton Harbour (median ~ 9 g m^{-3}). Charteris Bay had median TSS similar to the upper reaches of the Lyttelton Harbour main channel (~ 20 g m^{-3}).

2. Although there was substantial variability in TSS at a given location from day-to-day, concentrations of satellite-derived TSS were generally high (> 5 g m^{-3}) through most of Lyttelton Harbour for most of the time. For a given distance along Lyttelton Harbour, the variation between the 5th and 95th percentiles of TSS derived from the satellite data was a factor of ~3.6, with the 5th percentile being about 50% of the median (24–55%) and the 95th percentile being about 180% of the median (155–210%).

3. 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, though 3 pixels out of 385 had a trend that was significant at the 1% confidence level.

The main recommendations arising from this study are:

1. To improve comparisons between TSS measured *in situ* and by satellites: (a) match water sampling to cloud free conditions; (b) sample close to the centre of the Lyttelton Harbour channel in deep water; (c) sample close to the time of satellite overpass (around 1330 local solar time for MODIS Aqua); (d) carry out sampling in Port Levy.

2. Field sampling which complements satellite remote-sensing could include: (a) shore based sampling which provides information on TSS in areas of Lyttelton Harbour that the satellite cannot see; (b) sampling in shallow water where the satellite images are contaminated by the sea-bed being visible; and (c) an optical mooring in Lyttelton Harbour which would reduce bias in satellite data caused by covariance between TSS and cloud cover.

3. We recommend that Environment Canterbury consider whether more focus on measuring optical attributes *in situ* would be useful instead of, or as well as, TSS. Secchi depth and turbidity are already measured and should be continued. 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). As well as being estimated more accurately by satellite sensors than TSS, optical parameters like water clarity may relate more closely to ecological and human-use impacts of fine suspended matter.

1 Introduction

1.1 Background

Environment Canterbury (Environment Canterbury) seeks to use ocean colour satellite imagery to assist in management of the Lyttelton Harbour and Port Levy ("study region", Figure 1-1). Oceanographic and hydrological processes in the coastal zone are highly dynamic. "Coloured" or light-attenuating material is introduced, transported, transformed and removed in estuaries and coastal waters by a variety of processes and at different spatial and temporal scales. Water sampling using *in situ* methods (such as from the shore, vessels, helicopters, moorings) has limited ability to assess or monitor large-scale patterns (100s of km) of optical or biogeochemical properties of estuaries over long periods (decades).

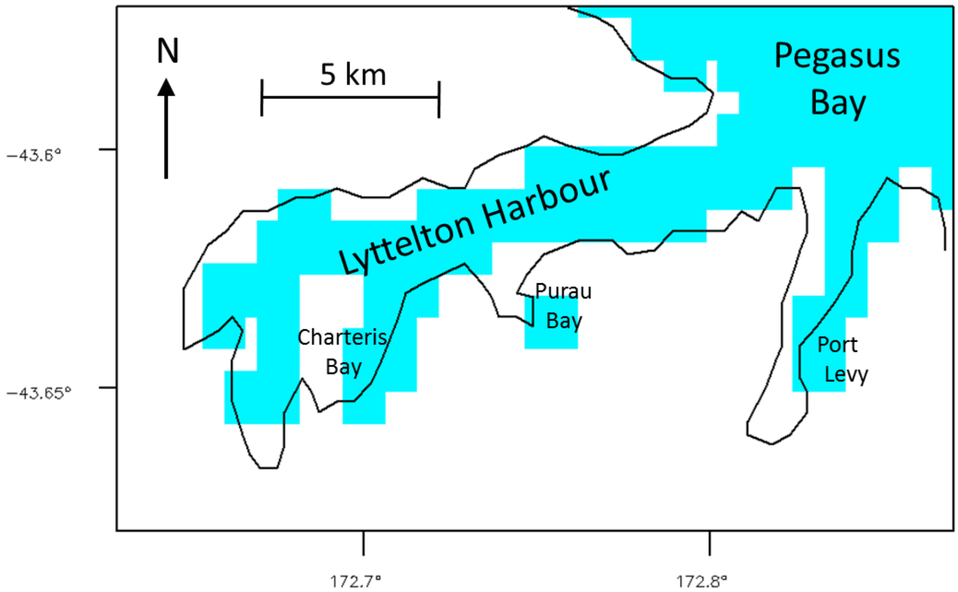


Figure 1-1: Map of study area, showing Lyttelton Harbour and Port Levy. The blue shading shows the areas for which MODIS-Aqua data are potentially available. Note that the geolocation accuracy of satellite data like this is approximately ±500 m, so that when satellite data are projected onto a latitude-longitude grid, small features (such as Purau Bay and Port Levy) in the satellite data can misalign with the coastline. This is not necessarily a problem, but can introduce errors to match-up analysis with *in situ* measurements.

Satellite ocean colour data can complement *in situ* sampling by observing light-attenuating material in coastal regions on appropriate time and space scales. The main light-attenuating material in coastal waters – phytoplankton (via the proxy of chlorophyll-a concentration, chl-a), total suspended solids (TSS) and coloured dissolved organic matter (CDOM; aka gilvin) – have different optical (absorbing and scattering) properties (Jerlov, 1974; Morel & Prieur, 1977; Mobley, 1994) and hence affect the colour of water in different ways (Figure 1-2). By measuring the colour of the water from sensors on earth-orbiting satellites it is possible to map the distributions of these components in a near-synoptic way, over large areas and at a high frequency (up to daily should clear skies allow). Compiling data over periods of years allows variability, trends and mean distributions of coloured water constituents to be assessed.

However, variations in the optical properties of material in seawater in different regions can lead to large errors in satellite estimates of concentrations of TSS. Local bio-optical data must be collected to test and, if necessary, locally tune the satellite processing methods. This has been called “water truthing” or “ground truthing” satellite images.

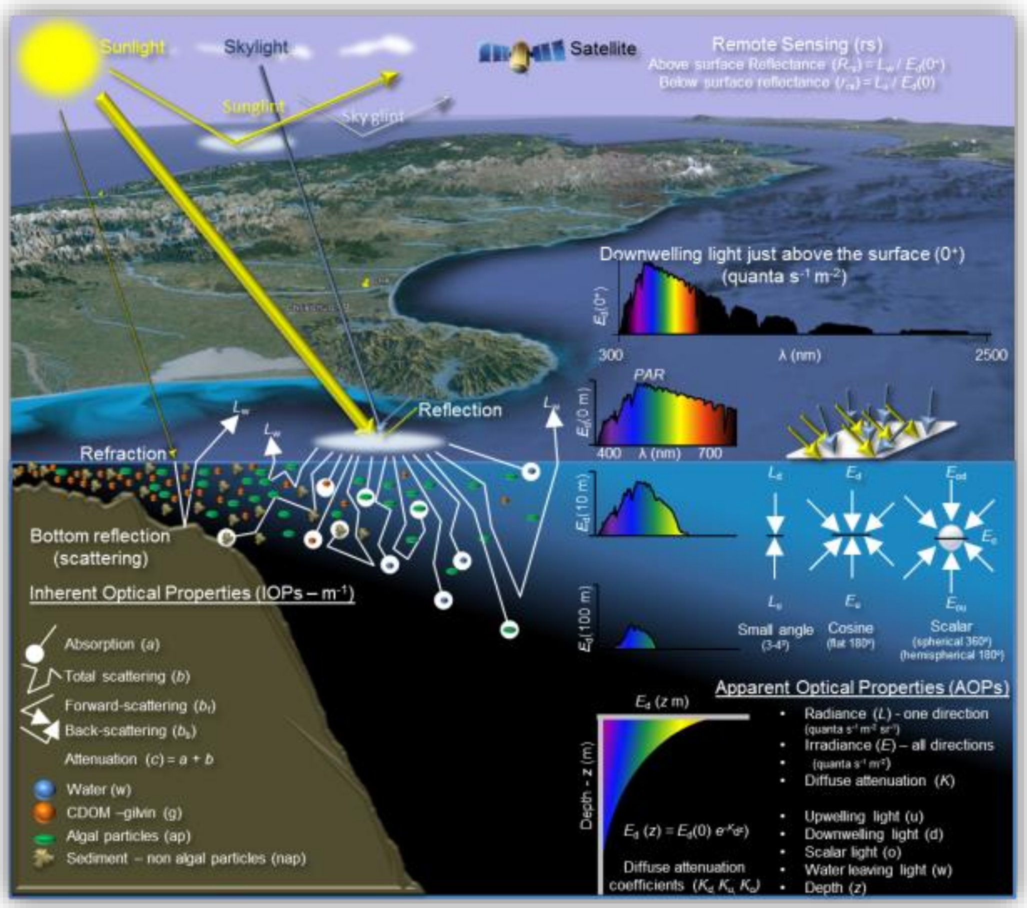


Figure 1-2: The fate of sunlight and skylight entering a water body. A schematic of the fate of light in seawater, including its interactions (surface, water, gilvin, algal particles, sediment particles and the sea-bed) and the optical properties used to describe these interactions. Inherent Optical Properties (IOPs) are expressed independently of the ambient light characteristics, as opposed to Apparent Optical Properties (AOPs). The ability of light to penetrate to depth is dependent on absorption and scattering properties. The deep clear ‘blue’ ocean, water absorption dominates these properties leading to high attenuation of longer wavelength light (red).

1.2 Objectives

This study had two objectives:

1. Use measurements of the biogeo-optical and biogeochemical properties of surface water in the study region to evaluate the empirical and semi-analytical satellite data products available, including, if necessary, tuning available algorithms to the *in situ* data.
2. Assess the distribution and concentrations of TSS over the past decade in the study region. Provide these data to Environment Canterbury to aid spatial planning and management.

1.3 Structure of report

Section 2 gives details of the satellite measurement methods and background to the remote sensing method. Section 3 presents local measurements of biogeo-optical and biogeochemical parameters in the study area, and reports on the use of these measurements to validate and locally tune ocean colour processing algorithms. Section 4 presents satellite ocean colour observations for TSS in the study region. Satellite data were used to describe the present and recent-historical state of water quality in this region, in the context of its spatial and temporal variability. Section 5 discusses and summarises the results. Section 6 gives conclusions and Section 7 provides some recommendations for sampling to complement remote sensing methods.

2 Remote sensing of ocean colour

2.1 Light-attenuating water constituents

What we observe as the colour and clarity of natural waters (apparent optical properties) arise from the inherent optical properties (IOPs, light absorption and scattering) of water itself, its solutes (dissolved substances) and suspended particulates, and the direction, wavelength and intensity of the incident sunlight illumination (Kirk, 2011; Figure 1-2). Light-attenuating components are grouped depending on methodological determination: total suspended solids (TSS) encompasses all mass captured by the gravimetric technique, and is likely to be dominated by refractory material in the study region; phytoplankton or algae are typically represented by the concentration of its major photosynthetic pigment chlorophyll-*a* (chl-a); non-algal particles (NAP) represent mineral sediments and particulate detritus/organic breakdown products) measured after removing pigments; coloured dissolved organic matter (CDOM or gilvin) is the remaining colour once the most light-scattering particulates have been removed by filtering at 0.2 μm. Images from ocean colour satellites is typically used to map coloured material in the surface water in these three categories:

1. **Total suspended solids (TSS)** – includes suspended organic and inorganic particulates (but not colloids/nano-particles which pass through filters). Non-algal particles (NAP) in the water column are a complex mixture of living and non-living material arising from local production processes within the water column (autochthonous) and material brought in from elsewhere (allochthonous). NAP can be introduced to the water column in river water, by

shore erosion and/or by re-suspension of sediment from the sea-bed. The terrigenous particulate material includes both mineral sediment particles and organic detritus. Over timescales of a few days, phytoplankton die, are grazed by zooplankton, and/or are degraded by viral and bacterial lysis. These degradation processes lead to local formation of particulate organic matter which forms part of the non-algal particle assemblage. Naturally occurring TSS in the region contains both organic (“volatile suspended solids”, VSS) and inorganic (non-volatile) particulates.

2. **Phytoplankton** - Phytoplankton growth forms algal cells in the upper water column by photosynthesis. Different species of phytoplankton contain various mixtures of pigments - the coloured chemicals which phytoplankton use to absorb light. However, as all phytoplankton contain chlorophyll-a (chl-a, mg m^{-3}), which is typically the dominant pigment in terms of absorption, spectral signatures are similar. Although chl-a is a convenient biomarker for phytoplankton biomass, the ratio between total phytoplankton biomass and chlorophyll varies between species of phytoplankton (e.g., Falkowski & Raven 1997; Kirk, 2011) and in response to light acclimation and nutrient limitation (Geider et al. 1997; Macintyre et al. 2002).

3. **Coloured dissolved organic matter (CDOM)** – CDOM is humic material (humic and fulvic acids, that are polymers of a wide range of low molecular weight organic chemicals) formed by the natural breakdown of organic material in soil or aquatic environments. CDOM in the study region will derive from (1) humic matter of terrigineous origin (allochthonous) introduced to the coastal zone from rivers and (2) the local breakdown of phytoplankton, zooplankton and other living material. CDOM from these two sources are generally optically indistinguishable, although they may be chemically distinguishable. The shape of the absorption spectrum of CDOM is also typically very similar to that of NAP, being highest in the blue and decreasing in an approximately exponential pattern to the red end of the visible spectrum.

2.2 Source of satellite imagery

All ocean colour satellite imagery used in this report are from the Moderate Resolution Imaging Spectrometer (MODIS), on the Aqua satellite, owned and operated by the US National Aeronautics and Space Administration (NASA). This imagery is most suitable for remote-sensing of Lyttelton Harbour because it has reasonable spatial resolution (250 m in key spectral bands), sufficient numbers of spectral bands with enough sensitivity to detect subtle changes to water colour, and frequent overpasses (daily). MODIS-Aqua images are also freely available and their processing is supported by NASA. Satellite sensors with higher spatial resolution (e.g. LANDSAT) typically do not have enough spectral bands or enough sensitivity to measure ocean colour accurately enough to estimate TSS. Sensors with high spatial resolution and many spectral bands (e.g. hyperspectral sensors such as SPOT) do not have daily overpasses and are often “pay-per-view”. Other satellite sensors which are similar to MODIS-Aqua in their design tend to have problems with sensor characterisation that leads to poor quality images (MODIS-Terra) or lower spatial resolution (SeaWiFS, MERIS).

Images from MODIS-Aqua used in this study cover the period between when MODIS-Aqua became operational on 4th July 2002 until 9th April 2014. Level 1A (top of atmosphere, uncalibrated) MODIS-Aqua data were acquired from the Ocean Biology Processing Group at NASA by file transfer between 4th July 2002 and the end of 2007. These data were obtained as full spatial-resolution 5-minute "granules" (sections of the overpass 5 minutes long). From the start of 2008 to 9th April 2014, satellite images were received directly from the satellite as it passed over New Zealand using the NIWA direct-broadcast satellite receiver in Lauder. All direct broadcast data were calibrated and processed to images using NASA calibration files series 6 (v6.1.17). In total we had 4278 individual data files, usually one and sometimes two per day Each file contains all MODIS-Aqua spectral bands for the study region. This is different than the number of days for three reasons: (1) there were often 2 overpasses of the study region (or part of the study region) per day; (2) before direct broadcast data were available, sometimes more than one 5-minute granule were needed to cover the study region; (3) occasionally data were not received from the satellite or data were corrupt and could not be processed.

2.3 Satellite data grid

All parameters were calculated at a spatial resolution of 250 x 250 m, using one MODIS band with 250 x 250 m resolution, one with 500 x 500 m resolution and the remaining colour bands at 1000 x 1000 m resolution. All derived data products were mapped onto a grid which had 0.00225° resolution in latitude and 0.0031° resolution in longitude. The centre points of the pixels in the study area were from 172.5°E to 173.2° E, and 43.4° S to 43.7° S. This area was selected to cover the Lyttelton Harbour and Port Levy area. The number of pixels in the grid was 227 (x) by 135 (y), giving a total of 30,645 pixels per image.

2.4 Atmospheric correction

Top-of-atmosphere satellite data must be calibrated and corrected for atmospheric absorption and scattering as light transmits between sea level and the satellite radiometer. About 80–95% of the signal received by a radiometric sensor at the top of the atmosphere is from light scattered in the atmosphere and not from the sea at all (Gordon, 1997). In order to obtain the colour of the water, and hence estimate water constituents, it is necessary to remove the atmospheric scattering contribution. Waters with low concentrations of suspended particulates are black in the near infra-red (NIR) because of the high absorption by pure water at these wavelengths. Atmospheric correction exploits this fact to estimate the contribution from the atmosphere. In coastal waters, this method fails because suspended solids reflect red and NIR light out of the water and invalidates the usual atmospheric correction method. Hence, methods that correct for atmospheric radiance at the top of the atmosphere, whilst allowing for non-negligible water leaving radiance in the NIR, are required for remote sensing in coastal regions (e.g. Lavender et al., 2005; Wang & Shi, 2007). A variety of atmospheric correction methods designed for turbid waters are available (e.g. Ruddick et al., 2000; Lavender et al., 2005) or are under development (Pinkerton unpublished data), but only one is currently supported by NASA for use with MODIS data, the NIR-short-wave infrared radiation (SWIR) switching algorithm (Wang & Shi, 2007). In this study therefore, atmospheric correction was applied following Wang & Shi (2007) to maximise sensitivity to small-scale variability in aerosols near-shore. This algorithm uses longer wavelengths that are not affected by TSS, to estimate scattering by atmospheric aerosols. A drawback is that the NIR-SWIR is less reliable than the standard NIR algorithm because the optical effects of aerosols in the atmosphere must be extrapolated over a longer spectral distance. This leads to a higher failure rate in the satellite images. We note that atmospheric correction of ocean data over turbid and near-coast regions is an area of active international research and better methods for atmospheric correction over turbid waters may become available in the future. We are currently testing an alternative approach to atmospheric correction over turbid waters at NIWA.

2.5 In-water algorithms

Having obtained an estimate of water-leaving radiance in several wavebands (which constitutes a single measurement of “ocean colour”), the next step is to estimate the concentrations of light-attenuating materials in the water giving rise to this water colour. Traditionally, empirical “band-ratio” algorithms have been used. These simply use the ratio of water-leaving radiance in two or more wavebands together with empirically-derived coefficients to estimate a property of interest, such as chl-a concentration (e.g. O’Reilly et al.,1998) or TSS (e.g. Clark, 1997). Because the optical properties of material (especially TSS) vary substantially between regions, empirical “band-ratio” algorithms typically perform poorly in coastal waters where the optical properties of the material are different to that used to develop the band-ratio algorithm (Pinkerton et al., 2005). Even if substantial and appropriate local bio-optical data are available for local tuning of empirical algorithms, a fundamental limit on the accuracy of the data is set by the variability between the actual radiometric relationships and the simple band-ratio construct.

Semi-analytical (or “quasi-analytical”) algorithms address these issues by de-convolving remotely sensed reflectance spectra simultaneously into contributions by all potential light-attenuating constituents using appropriate radiometric relationships. The methods retain an empirical component: they assume typical spectral shapes for the absorption and scattering properties of phytoplankton, dissolved substances and inorganic particulates. These reflectance-IOP relationships appear to be regionally robust and insensitive to material types, (Garver & Siegel, 1997; Lee et al., 2002).

Semi-empirical algorithms also require the conversion of IOPs to biogeo-optical values such as chl-a concentration and TSS. The relationship of IOPs to biogeochemical constituents is complicated and dependant on the suspended particulate and dissolved solute characteristics. Typical particle characteristics which determine IOPs are the particle size distribution, shape and refractive index (Boss et al. 2001, Twardowski et al. 2001), together with phytoplankton community composition and pigment packaging effects (Babin et al. 2003b, Babin et al. 2003a, Lohrenz et al. 2003 and Bricaud et al. 2004). Solute IOP characteristics are determined mainly by the concentration of CDOM and its composition (e.g. Coble et al. 2004). As the optical signatures of the biogeochemical components are not entirely separable in the bulk IOPs based on spectral signatures alone, local information on these IOP-concentration relationships are needed (e.g. Babin et al. 2003b, Richardson et al. 2004; Pinkerton et al. 2005).

3 Objective 1: Evaluation of satellite products

3.1 *In situ* data

Two sets of *in situ* data were used in this project: (1) data made available by Environment Canterbury; (2) data measured using NIWA core funding based on sampling by the National River Water Quality Network (NRWQN; Davies-Colley et al. 2011).

3.1.1 Environment Canterbury water quality data

Environment Canterbury made available data on water clarity, TSS, volatile suspended solids (VSS) and turbidity in coastal water from Lyttelton Harbour/Whakaraupō and 3 km from the shore in Pegasus Bay (Table 3-1, Table 3-2). Sample locations are shown in Figure 3-1. Water samples were collected from a depth of 20-30 cm, from all of boat sampling, helicopter sampling and shore-based sampling. Turbidity was measured either by the Environment Canterbury laboratory or by Hill Laboratories using APHA 2130B turbidity meter calibrated to normalised turbidity units (NTU). Total suspended solids (TSS, g m^{-3}) was measured gravimetrically either by the Environment Canterbury laboratory or by Hill Laboratories. Volatile suspended solids (VSS, g m^{-3}) was calculated from loss of weight on combustion (exact methodology not provided) but these data are not used in the present study Secchi depth (m) was measured in the field but is not used in the present work.

Table 3-1: Numbers of data points provided by Environment Canterbury. TSS = Total Suspended Solids. VSS = Volatile Suspended Solids. NTU = Normalised turbidity units.

Platform	Number stations	Start date End date	Number samples	Statistic	Secchi depth (m)	TSS (g m^{-3})	Turbidity (NTU)	VSS (g m^{-3})
Boat or helicopter in Lyttelton Harbour	13	29/07/2002 10/12/2013	523	Number	243	446	522	167
				Minimum	0.15	1.9	0.46	0.7
				Median	0.8	15	5.25	2
				Maximum	6.5	180	75	16
Pegasus Bay	3	19/09/2007 10/12/2013	84	Number	0	80	84	0
				Minimum		3.5	0.28	
				Median		8.05	2	
				Maximum		46	13	
Shore-based sampling	5	11/07/2011 14/06/2013	114	Number	90	114	114	89
				Minimum	0.02	4	0.95	0.6
				Median	0.565	25	9.05	3
				Maximum	1.5	1500	400	69

Table 3-2: Sites from which data were provided by Environment Canterbury. Sampling from boat/helicopter (13 sites) and from the shore (5 sites) were in Lyttelton Harbour, with an additional three sites in Pegasus Bay.

Platform	Site	Latitude °S	Longitude °E
Boat or helicopter in Lyttelton Harbour	SQ30651	43.6261	172.6578
	SQ35146	43.6167	172.6833
	SQ35147	43.6306	172.7156
	SQ35788	43.6086	172.7422
	SQ30635	43.6172	172.7236
	SQ35148	43.6119	172.7481
	SQ32587	43.6014	172.8103
	SQ30636	43.6111	172.7297
	SQ30661	43.6397	172.7000
	SQ30632	43.6100	172.6975
	SQ35187	43.6200	172.7072
	SQ30680	43.6094	172.7164
	SQ30673	43.6300	172.7483
Pegasus Bay	SQ35184	43.2878	172.7597
	SQ35185	43.3933	172.7492
	SQ35186	43.4981	172.7669
Shore-based sampling	SQ35787	43.6122	172.7064
	SQ35065	43.6081	172.6811
	SQ30650	43.6278	172.6531
	SQ30662	43.6336	172.7175
	SQ30666	43.6236	172.7364

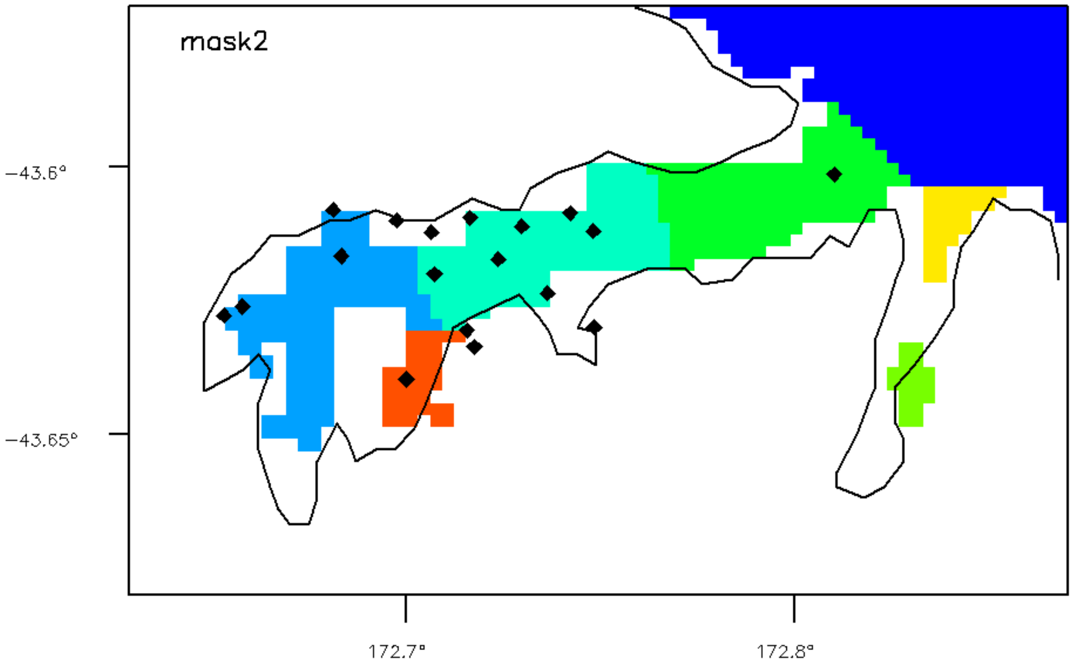


Figure 3-1: Locations of sampling by Environment Canterbury and sub-regions defined for the purposes of this study. *In situ* sampling locations in Lyttelton Harbour (see Table 3-2) are shown as black diamonds. Sub-regions: Lyttelton Harbour upper (mid blue), middle (cyan), lower (dark green); Port Levy upper (light green), lower (yellow); Charteris Bay (orange). Areas where there were no satellite data over the period 2002 - 2014 are shown white. Areas where there were satellite data but are outside the focus area of this study are shown in dark blue. See also Table 4-1 for definition of the sub-regions.

3.1.2 Optical measurements added onto the National Rivers Water Quality Network

Since the implementation of the National River Water Quality Network (NRWQN) in 1989, water has been collected approximately monthly from 49 of New Zealand's major rivers at 77 sites (Davies-Colley et al., 2011; Ballantine & Davies-Colley, 2013; Maasdam & Smith 1994; Smith & Maasdam 1994). The NRWQN has provided information on physico-chemical trends (Smith et al. 1996), water clarity and colour (Davies-Colley 1988; Davies-Colley 1990; Davies-Colley & Close 1990; Davies-Colley & Nagels 2008; Davies-Colley et al. 1997) and optical characteristics in relation to flow (Smith et al. 1997). Additionally, the relationships between routine optical variables in the NRWQN and TSS have recently been explored (Davies-Colley et al. 2014).

The mouth of Waimakariri River, which flows into Pegasus Bay to the north of Christchurch, has been regularly sampled as part of the NRWQN at site code "CH4" (43.41730°S 172.64177°E). Between 19 September 2007 and 17 September 2008, on 13 occasions, water samples collected from the Waimakariri were analysed for biogeo-optical properties at NIWA's optical laboratory in Christchurch (Gall, unpublished data). Analyses used in the present study are summarised in Table 3.3.

Table 3-3: Summary of selected biogeo-optical measurements for the Waimakariri and other major New Zealand rivers from the NRWQN. The National River Water Quality Network (NRWQN) samples water from 77 sites on 49 of New Zealand's major rivers. Biogeo-optical measurements were made between September 2007 and September 2008. Only a summary of measurements (those used in the present study) are given. NRWQN site “CH4” is at the mouth of the Waimakariri River, close to the study area.

Measure [units]	**Method**		**All**	**CH4**
TSS [g m^{-3}]	Total suspended solids (TSS) and volatile suspended solids (VSS) measured gravimetrically. Material collected on pre-washed, dried and weighed 25 mm Whatman GFF filters and stored frozen. Filters rinsed with three washings of nano-pure water (10-15 ml) to remove salt. Suspended particulate matter by weight was determined before and after drying (60°C, 12 hr) and combustion (450°C, 4 hr). Inter-comparison with TSS measured on polycarbonate filters for data quality checks.	Number	242	13
		Minimum	0.352	2.17
		Median	4.92	19.3
		Maximum	3344	3344
b_{bp}(660) [m^{-1}]	Backscatter (at 117° and 660 nm) were measured using an ECO-Triplet (Wetlabs Inc.). Nano-pure water used as a diluent when backscattering saturated the instrument response. Homogeneity maintained using a magnetic stirrer, for a one minute collection period. Water temperature and conductivity recorded for data processing. Manufacturer supplied calibration (using microspherical scatterers) and dark offsets used. Data processed according to Boss & Pegau (2001).	Number	244	13
		Minimum	0.00184	0.0266
		Median	0.0644	0.477
		Maximum	23.8	23.8
Turbidity [NTU]	Index of the 90° (side) scattering of light. Turbidity was measured on a HACH 2100AN, standardised to formazin nephelometric turbidity units (NTU).	Number	267	13
		Minimum	0.45	0.95
		Median	3.5	18.5
		Maximum	1800	1800
Normalised scattering *b*(660)/*b*(488)	Absorption (a) and beam attenuation (c) measured at 9 wavelengths over a 25 cm pathlength using an ac-9 instrument (Wetlabs Inc.). Water debubbled and recirculated using dual head peristaltic pump (Masterflex), with inflow to ac-9 at bottom inlet tubes. Samples diluted with temperature equilibrated, degassed nano-pure water when required. Calibration, operation, processing as manufacturer’s protocol (Wetlabs 2009). Scattering, b(λ)=c(λ)-a(λ), where *a* was derived preferentially from filter-pad measurements rather than ac-9 data (Gall, unpublished data).	Number	236	13
		Minimum	0.617	0.694
		Median	0.789	0.780
		Maximum	0.944	0.859
Normalised scattering *b*(660)/*b*(555)		Number	236	13
		Minimum	0.747	0.809
		Median	0.865	0.866
		Maximum	0.964	0.911

3.2 Satellite algorithms for total suspended matter (TSS)

We focussed on semi-analytical inversion algorithms currently supported by NASA SeaDAS v6.1. As explained in Section 2.5, semi-analytical algorithms provide a more robust relationship between the satellite observation of ocean colour and water constituents than band-ratio algorithms. There are a large number of other semi-analytical ocean colour algorithms and products available at the time of writing for in-water inversion which are not currently supported by NASA and that we did not consider (e.g. Pinkerton et al., 2006; Doerffer & Schiller, 2007; Shanmugan, 2011). The two semi-analytical satellite products from which to estimate TSS that we considered were:

1. Backscatter of particulate material at 555 nm ($b_{bp}(555)$, m^{-1}) estimated by the Garver-Siegel-Maritorena (GSM) algorithm (Garver & Siegel 1997; updated processing available from: www.icess.ucsb.edu/OCisD/). This satellite product is called BBP_{GSM} where "BBP" refers to the fact that the property estimated is the particulate backscatter coefficient (b_{bp}).

2. Backscatter of particulate material at 488 nm ($b_{bp}(488)$, m^{-1}) estimated by the Quasi-Analytical Algorithm (QAA) algorithm update v5 (Lee et al., 2002; Lee et al., 2009). This satellite product is called BBP_{QAA} because it is again an estimate of the particulate backscatter coefficient.

To estimate TSS (g m^{-3}) from either of these satellite backscatter products, we need to know the TSS-specific backscatter coefficient, $b_{bp}^*(\lambda) = b_{bp}(\lambda)/TSS$, at the appropriate wavelength (488 nm for QAA and 555 nm for GSM). Backscatter at 660 nm and TSS were measured close to the mouth of the Waimakariri River as an 'add-on' to the NRWQN dataset, and this could be used to estimate $b_{bp}^*(\lambda)$, with the appropriate wavelength correction. However, there are only 13 measurements in this NRWQN CH4 dataset, and it is possible that the optical characteristics of suspended material may be very different between the mouth of the Waimakariri River and Lyttelton Harbour as the water (and sediment) will have come from different catchments.

Hence, here we used a three step process to estimate $b_{bp}^*(\lambda)$ in Lyttelton Harbour.

First, the whole NRWQN biogeo-optical dataset (~250 points) was used to relate backscattering at 660 nm, $b_{bp}(660)$, to turbidity (Figure 3-2). For a given type of turbidity instrument, this relationship is likely to be relatively robust to variations in the optical properties of the material, provided that the ratio of 90° side-scatter to backscatter remains nearly constant. This assumption is supported by the fact that the blue and red points give similar regressions in Figure 3-2.

Second, turbidity was related to TSS using the whole Environment Canterbury dataset (Figure 3-3). It is known that turbidity, even when well-calibrated to NTU, is somewhat dependant on the type of instrument used (Davies-Colley & Smith 2001). The same turbidity instrument (nephelometer) was used by NIWA in all NRWQN biogeo-optical sampling and this instrument is of a similar design to that used by Environment Canterbury/Hill Laboratory for water quality measurements (90° side-scattering of light, calibrated to NTU). Turbidity results are likely to be quantitatively comparable beween datasets. This is supported by the fact that the red diamonds showing the NRWQN turbidity-TSS relationship concord well with the fitted Environment Canterbury turbidity-TSS relationship in Figure 3-3. If the red diamonds formed a separate line from the Environment Canterbury data, this would suggest that either the turbidity measurements made by NIWA and Environment Canterbury were incompatible, or that the material measured in the two studies had different biogeo-optical properties (e.g. different values of b_{bp}^* or very different scattering phase functions). The consistency between the red diamonds and Environment Canterbury data in Figure 3-3 supports our assumption that the turbidity data in the two datasets are quantitatively consistent. The small difference between the turbidity-TSS relationship in the NRWQN data and the Environment Canterbury data in Figure 3-3 is consistent with material in the Waimakariri and Lyttelton Harbour having slightly different optical characteristics. The turbidity/TSS ratio in Lyttelton Harbour are typically less than unity (Figure 3-3), in contrast to many rivers (e.g. Davies-Colley et al. 2014), which may be related to salt-water flocculation. Third, we used measurements of total particulate scattering at different wavelengths from the biogeo-optical part of the NRWQMN to calculate the appropriate relationship between backscatter at 488 nm, 555 nm and 660 nm. Even though the backscatter spectrum of naturally-occurring particulates is relatively flat in the visible part of the spectrum (see Table 3-3), it is necessary to relate backscatter at the wavelength estimated by the satellite algorithms to that measured during the NRWQMN biogeo-optical sampling. As we did not have measurements of backscatter at different wavelengths, we assumed that the spectral variation in particulate backscatter followed the spectral variation of total particulate scattering. This is a reasonable assumption (Pinkerton et al., 2005).

Total suspended solid concentration (TSS) can be estimated from the satellite measurement of particulate backscattering at λ (BBP) by Equation 1. The method calculates particulate backscatter at 660 nm from the satellite measurement of particulate backscatter at 488 or 555 nm, estimates turbidity from particulate backscatter at 660 nm, and then calculates TSS from turbidity. In equation 1, X and x describe the fitted relationship between backscatter at 660 nm and turbidity (Figure 3-3). Similarly, Y and y describe the fitted relationship between turbidity and TSS (Figure 3-2). The value of $b_{bp}(660)/b_{bp}(\lambda)$ is obtained from the median spectral relationship shown in Figure 3-4. Note that there is no single value of the specific backscatter coefficient, $b_{bp}^*(\lambda)$ in this method; the TSS-specific backscatter coefficient varies non-linearly with backscatter and TSS.

$$TSS = Y\left[X\left[BBP\left(\frac{b_{bp}(660)}{b_{bp}(\lambda)} \right) \right]^{x} \right]^{y} \qquad \text{[Equation 1]}$$

Using the GSM algorithm, TSS can be estimated from BBP_{GSM} as equation 2. Total suspended solids can be estimated from BBP_{QAA} as equation 3.

$$TSS = 74.27 \times \mathrm{BBP_{GSM}}^{0.7203} \qquad \text{[Equation 2]}$$

$$TSS = 68.92 \times \mathrm{BBP_{QAA}}^{0.7203} \qquad \text{[Equation 3]}$$

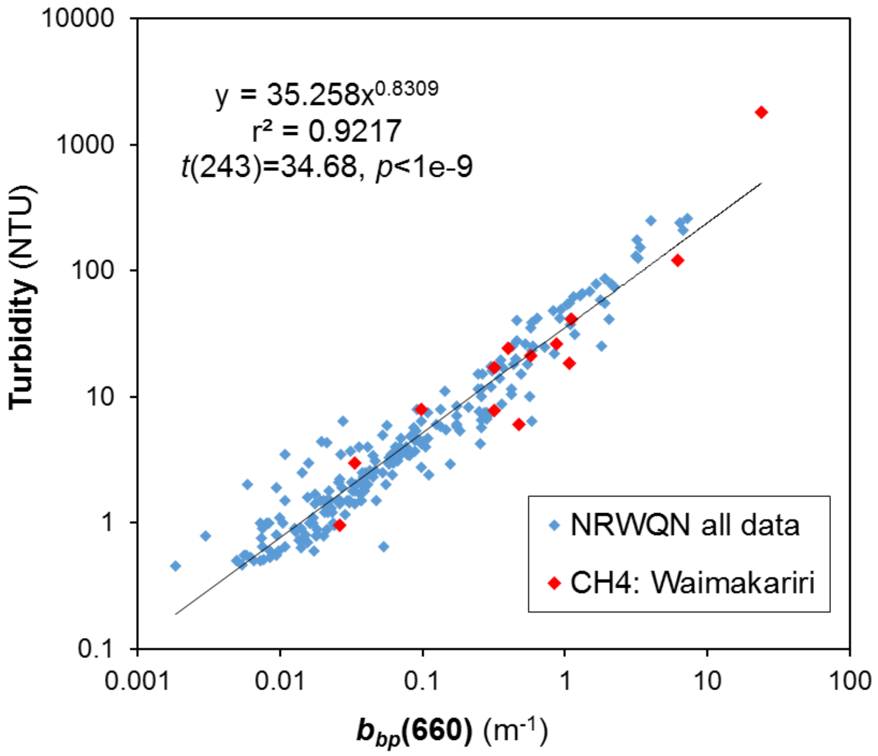


Figure 3-2: Relating particulate backscatter at 660 nm to turbidity (NTU) using the NRWQN biogeo-optical dataset. The whole National River Water Quality Network dataset is shown in blue and data from the mouth of the Waimakariri are shown as red diamonds. The regression line is significant at better than the 1% level in log-log space.

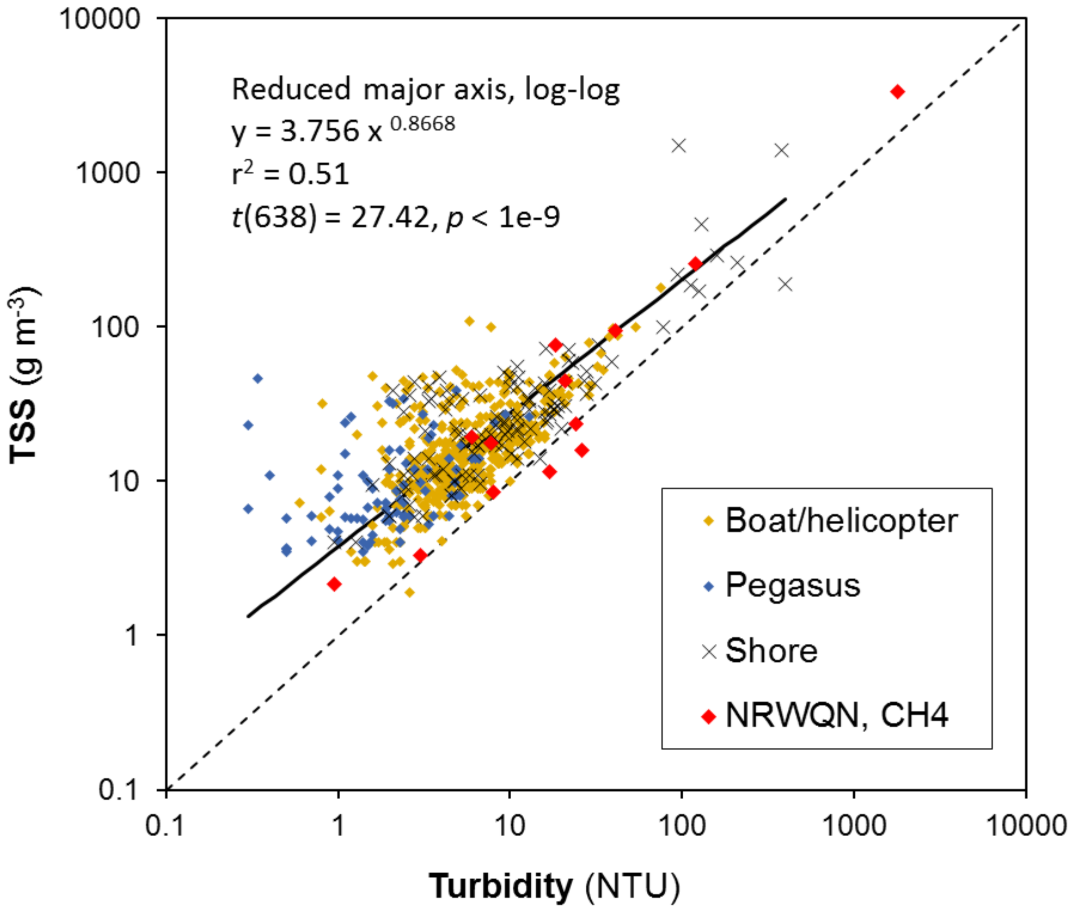


Figure 3-3: Relating turbidity (NTU) to total suspended solid concentration (TSS) using the Environment Canterbury dataset. The reduced major axis regression is fitted to the whole Environment Canterbury dataset (gold diamonds, blue diamonds, and crosses) in log-log space. The regression line is significant at better than the 1% level (evaluated in log-log space). The National River Water Quality Network (NRWQN) dataset at site CH4 (mouth of the Waimakariri River) is shown (red diamonds). Typical standard errors for TSS and turbidity are ~10%. The dashed line shows the 1:1 relationship for comparison.

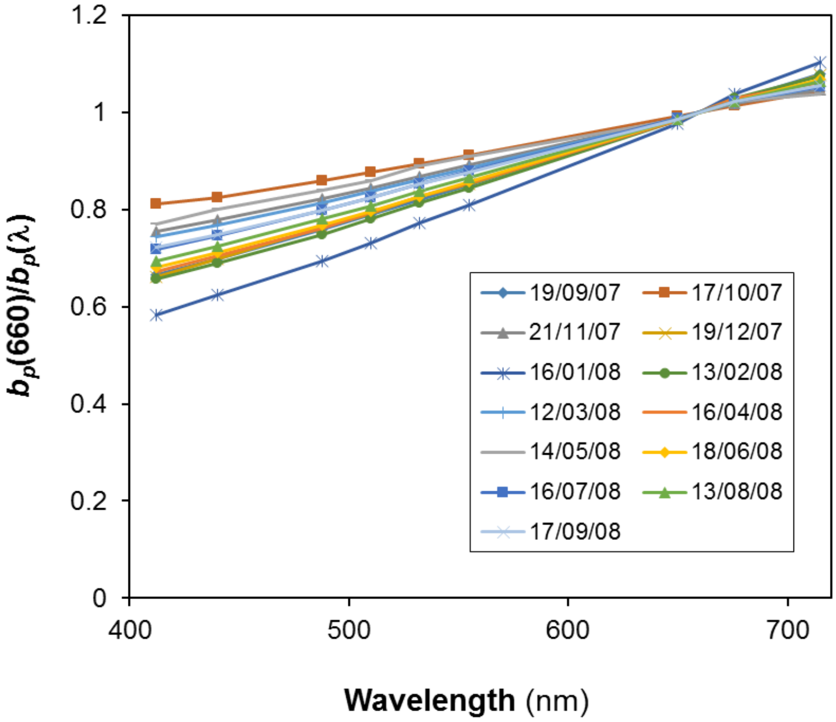
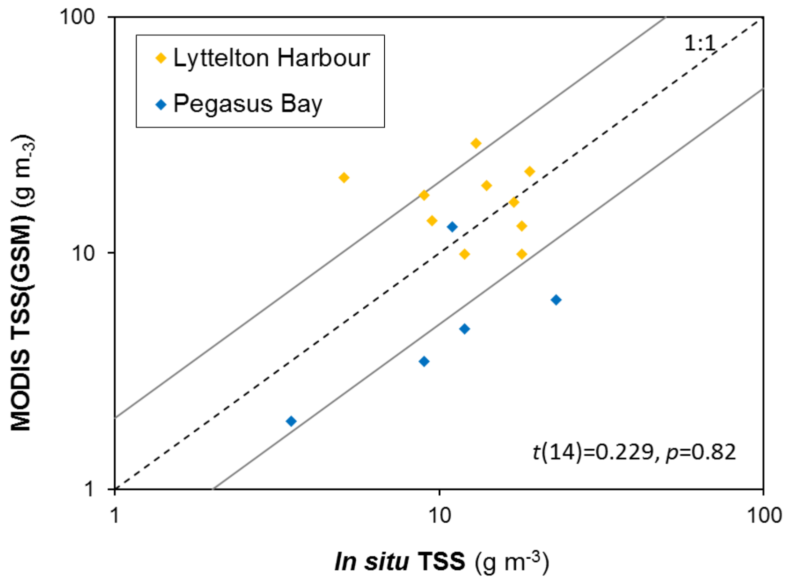


Figure 3-4: Spectral variation in the scattering coefficient of suspended particulate material at wavelength λ (nm) [$b_p(\lambda)$] to that at 660 nm. These data were measured on samples from near the mouth of the Waimakariri River. Measurements of the spectral scattering coefficient were made at 9 different wavelengths spanning the visible range using an ac-9 instrument on 13 monthly samples from the National River Water Quality Network (NRWQN) site CH4.

3.3 Comparing satellite and *in situ* TSS

Estimates of TSS derived from satellite measurements were compared to *in situ* measurements of TSS to provide an overall check on the quality of the satellite estimates of TSS. For a number of scientific and practical reasons (see Discussion), this “end-to-end” comparison or “match-up” analysis is likely to include only a few points and not lead to a close relationship. In this study we extracted all satellite measurements of the two candidate data products (BBP_{GSM} and BBP_{QAA}) at every available *in situ* measurement in the Environment Canterbury dataset. From 721 *in situ* measurements of TSS, there were satellite estimates of TSS only on 19 (BBP_{GSM}) or 20 (BBP_{QAA}) occasions. The number of comparisons differ between satellite products because they have different fail rates. Of these, 13 or 14 match-ups were in the Lyttelton area and 6 were in the Pegasus Bay region. Satellite data were extracted on the same day of sampling only. The average time difference between the satellite overpass and *in situ* sampling was 3.4 hours (1.0 – 5.3 h). The comparisons are shown in Figure 3-5. There was no statistically significant difference between the satellite-derived estimate of TSS and the *in situ* measurements.

a



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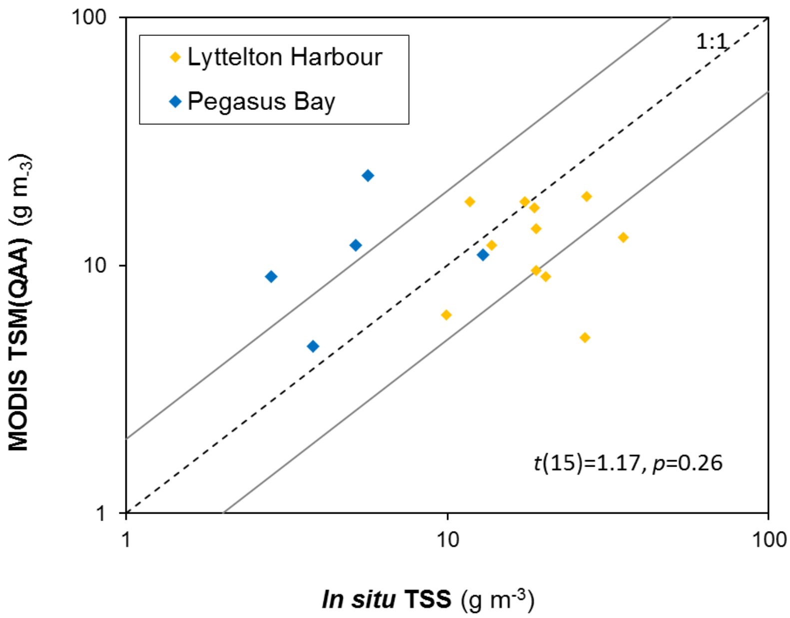


Figure 3-5: Comparison of satellite-derived estimates of TSS and *in situ* measurements by Environment Canterbury. *In situ* measurements of gravimetric total suspended solids (g m^{-3}) and two candidate satellite products: (a) TSS derived from applying the Garver-Siegel-Maritorena (GSM) algorithm to MODIS-Aqua data as described in the text. (b) TSS derived from applying the Quasi-Analytical Algorithm (QAA) to MODIS-Aqua data as described in the text. The dashed line is the 1:1 line. The t-test results indicate that we cannot reject the null hypothesis that the satellite-derived estimate of TSS and the *in situ* measurements are from the same distribution. The dashed line shows the 1:1 relationship and the grey lines indicate differences of a factor of 2.

3.4 Conclusions regarding satellite remote-sensing of TSS

Two available semi-analytical algorithms for particulate backscatter are supported in the current version of NASA's processing system (SeaDAS) for MODIS-Aqua: GSM and QAA. Using a combination of data supplied by Environment Canterbury, and data from NIWA's biogeo-optical core project based on the NRWQN, methods were developed to estimate TSS from both algorithms. These resulting algorithms were specific to the Lyttelton Harbour region. Comparisons between *in situ* data and satellite data on the same day were sparse. The satellite data in the comparisons were not statistically different from the *in situ* measurements,. The BBP_{GSM} product is limited to 0.3 m^{-1}, equivalent to an estimated TSS of about 30 g m^{-3}. This is lower than the highest values of TSS found in the study region. The 95^{th} percentile of the Environment Canterbury measurements of TSS was 51 g m^{-3}. The BBP_{QAA} product is not capped, and values >0.6 m^{-1} (equivalent to TSS ~50 g m^{-3}) were obtained in Lyttelton Harbour in this study. Also, the QAA algorithm provides slightly more retrievals than the GSM algorithm (by about 5%). Hence, for the purposes of this report, we select the scaled BBP_{QAA} product as being the better candidate for estimating TSS (equation 3).

4 Objective 2: Satellite total suspended solids

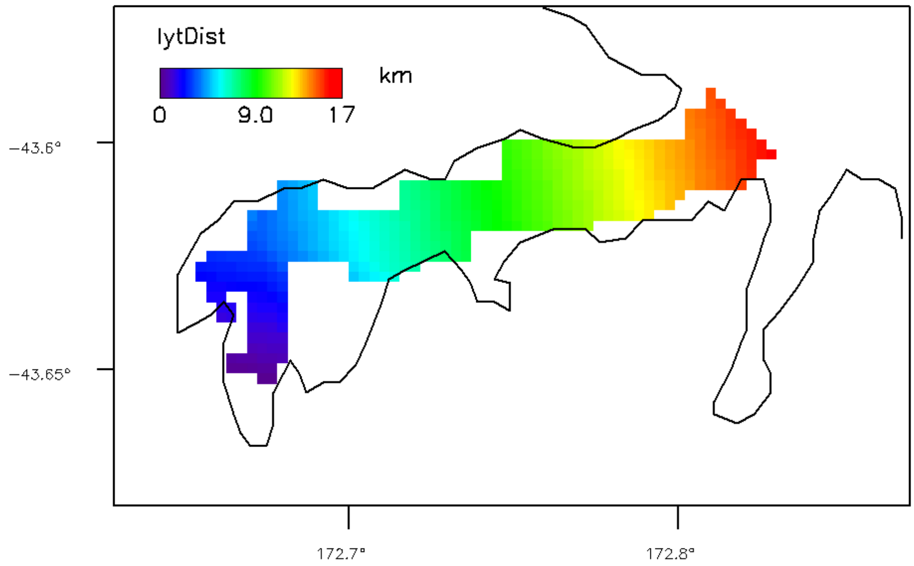
4.1 Regions in the descriptive analysis

Distances from the nominal head of the Lyttelton Harbour ("lytDist") and Port Levy ("levyDist") estuaries were calculated (values increasing along the axes, from zero at the highest point where MODIS measurements of TSS were available (Figure 4-1). These distances were used to define six sub-regions within the study region for descriptive analysis (Table 4-1, Figure 3-1).

Table 4-1: Sub-regions defined here for description of the satellite data. Distances along the axis of the Lyttelton Harbour and Port Levy were chosen to divide the areas approximately equally.

Sub-region	**Description**	**Area for which MODIS TSS data available** (km^2)
Lyttelton Upper	Lyttelton Harbour, *lytDist*<5.7 km	9.1
Lyttelton Middle	Lyttelton Harbour, *lytDist* 5.7-10.9 km	9.6
Lyttelton Lower	Lyttelton Harbour, *lytDist*>10/9 km	9.4
Levy Upper	Port Levy, *levyDist*<3 km	1.2
Levy Lower	Port Levy, *levyDist*>3 km	1.9
Charteris	Charteris Bay	2.2

a



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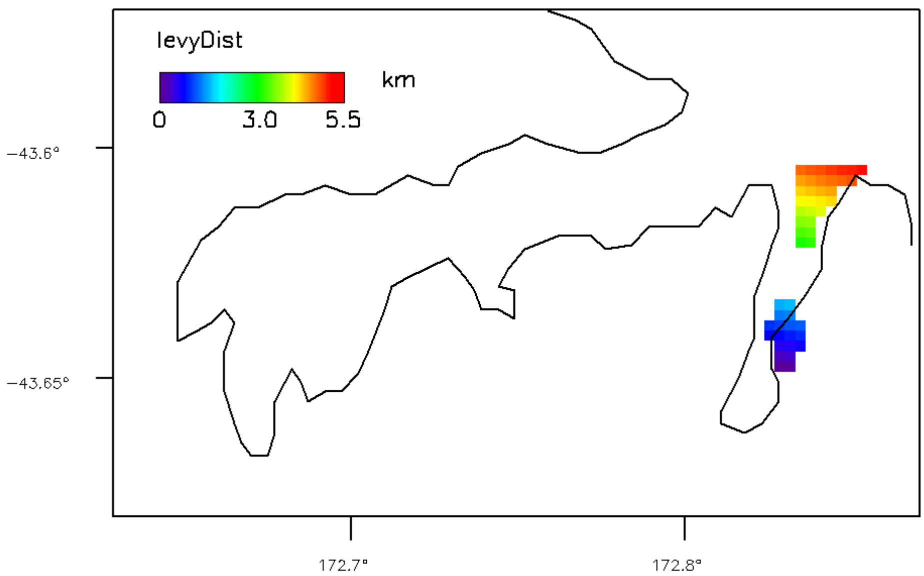


Figure 4-1: Distance along the main axis of a: Lyttelton Harbour; b: Port Levy. Distances are approximate km from the head of the estuary and are used for descriptive analysis.

4.2 Satellite data coverage

Of the 5418 MODIS-Aqua images considered in this study for the period July 2002 to April 2014, only 855 contained TSS data in the Lyttelton Harbour and Port Levy study area (Table 4-2). Data were not available because of cloud cover, algorithm failure, or, very rarely, satellite data were not available (because of instrument malfunction). These 855 files provided more than 58,000 estimates of TSS, equivalent to an average of 65 estimates per pixel in the study region. There were more estimates per pixel in the centre of the channel (maximum of 508 estimates per pixel) than the edges (Figure 4-2) as expected. Shallow water and the fact that pixels that clip the land lead to failure of satellite estimates mean than fewer satellite estimates of TSS should be expected close to shore.

There was a strong seasonal component to data availability (Figure 4-3), with more data available in the winter than summer. This pattern was unexpected and may be due to unusual seasonal variation in cloud cover in Lyttelton Harbour. This counter-intuitive seasonal pattern of clear satellite images did not occur over the larger Pegasus Bay area (data not shown) and warrants further investigation in the future. For Lyttelton Harbour, over the 11+ years of satellite data, there were a total of 9729 estimates of TSS in July (highest month) and 665 in December (lowest month).

Table 4-2: Number of MODIS-Aqua images and data points by year. The total number of MODIS-Aqua files for the Lyttelton Harbour and Port Levy regions, the number of files with any TSS data based on the QAA algorithm and the number of TSS data points by year. The proportion of valid data is also shown.

Year	Number images	Number images with valid TSS data	Number valid TSS pixels	Proportion pixels with TSS data (%)
2002	224	29	1460	7.0
2003	490	75	4513	8.3
2004	493	74	4950	9.2
2005	481	70	4566	9.0
2006	489	69	4130	8.3
2007	485	91	5802	8.8
2008	447	74	3841	7.2
2009	450	87	5882	9.3
2010	432	81	5556	9.5
2011	425	71	4863	9.5
2012	454	72	5635	10.8
2013	465	83	6617	11.0
2014	83	21	832	5.5
All	**5418**	**897**	**58,647**	**9.0**

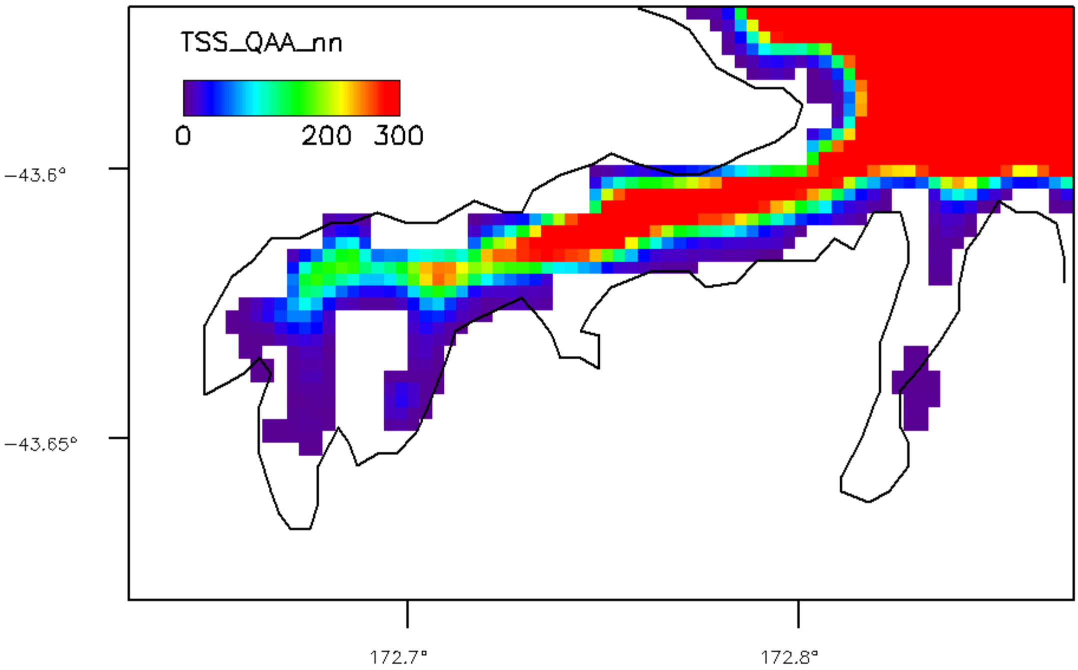


Figure 4-2: Number of estimates of TSS from MODIS-Aqua by location. There was a strong spatial variation in data availability (higher in the centre of the channel, lower towards the coast).

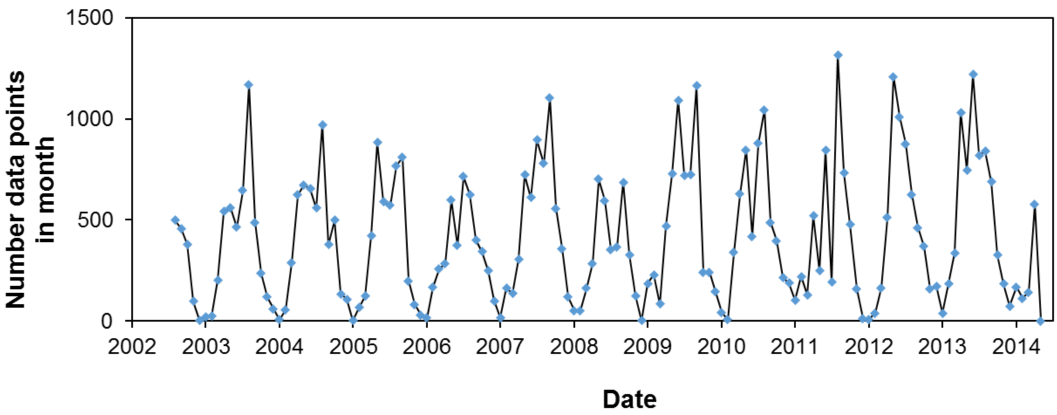


Figure 4-3: Number of measurements of TSS from MODIS-Aqua in the study area by date. There was a strong seasonal variation in data availability (lower in summer, higher in winter).

4.3 Long-term statistics of estimated TSS

Median TSS over the whole 11+ year dataset were calculated at each pixel in the study area (Figure 4-4). As TSS generally tends to be log-normally distributed, medians are likely to provide a better indication of typical conditions than the mean. Indicative high (95% percentile, Figure 4-5) and low (5% percentile, Figure 4-6) of TSS were calculated for each pixel using the full time series (July 2002 to April 2014). Percentiles were used because extreme maximum and minimum values can be affected by extreme single values.

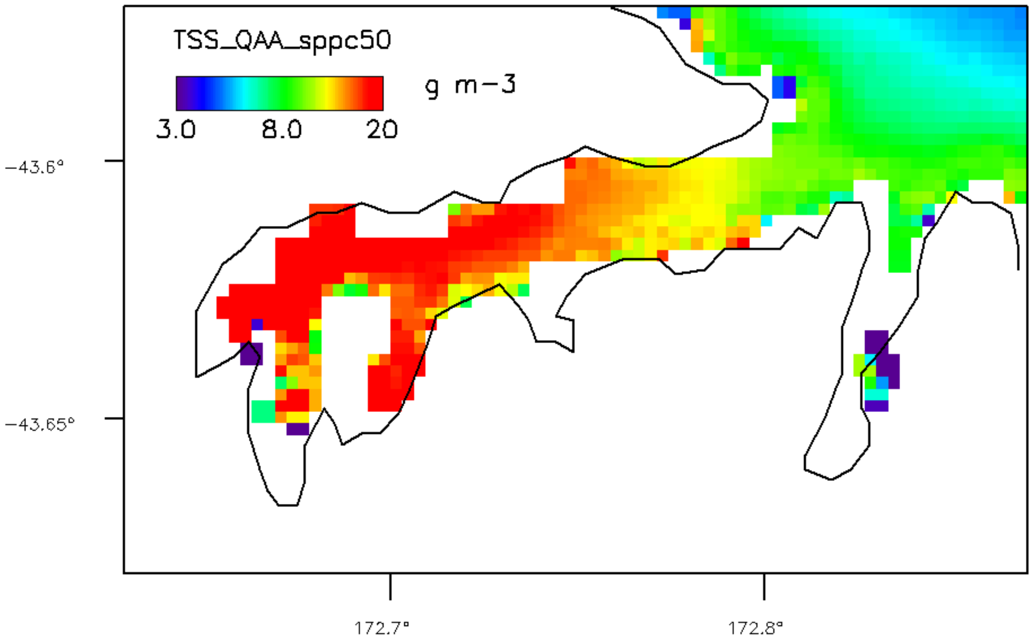


Figure 4-4: Long-term median TSS (g m^{-3}). Values calculated using the locally-tuned QAA algorithm (equation 3). Values were calculated as the median value over 11+ years of MODIS-Aqua data in each pixel. Note the logarithmic scale in concentration.

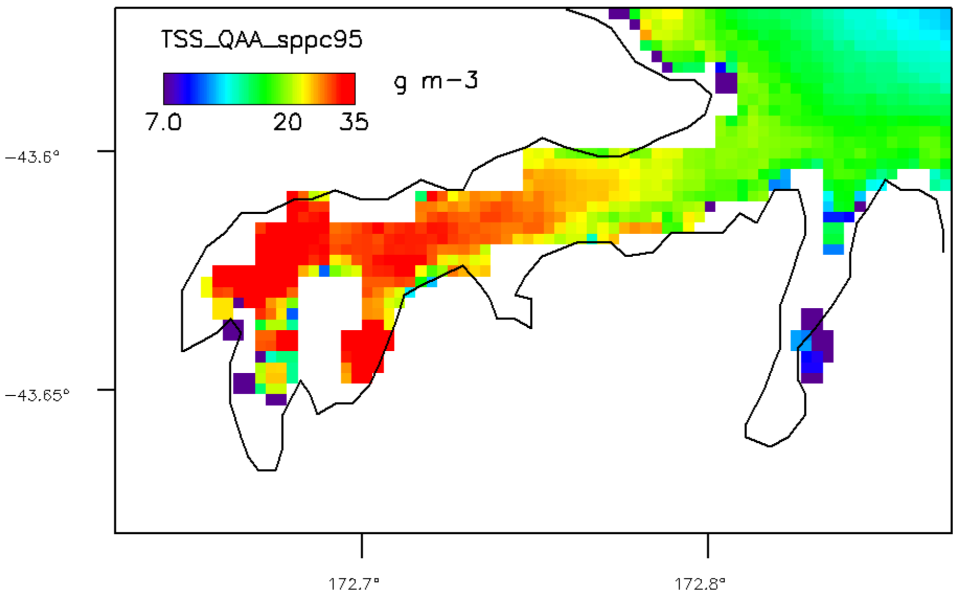


Figure 4-5: 95th percentiles of TSS (g m^{-3}). TSS estimated using the locally-tuned QAA algorithm (equation 3). Values are calculated as the 95th percentile at each pixel over 11+ years of MODIS-Aqua data. Note different scale to Figure 4-4 and Figure 4-6.

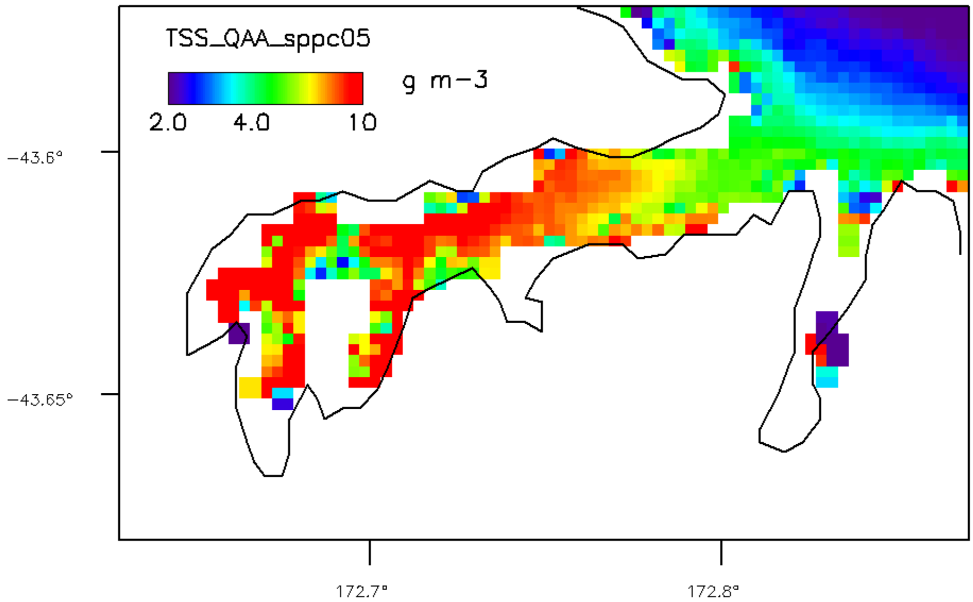


Figure 4-6: 5th percentiles of TSS (g m^{-3}). TSS estimated using the locally-tuned QAA algorithm (equation 3). Values are calculated as the 5th percentile at each pixel over 11+ years of MODIS-Aqua data. Note different scale to Figure 4-4 and Figure 4-5.

4.4 Regional comparison

Total suspended solids derived from satellite data agree well with *in situ* sampling by Environment Canterbury in the Lyttellton Harbour and Charteris Bay regions in an overall statistical sense (Figure 4-7). In all 4 cases (upper, middle, lower Lyttelton Harbour and Charteris Bay) the 5th – 95th percentile of the TSS values derived from satellite data overlaid the median of the *in situ* sampling. The interquartile range of the satellite-derived estimates of TSS were lower than the range for the *in situ* sampling. This could be because the satellite measurements are effectively sampling a much larger area average (250 m x 250 m) than the *in situ* samples (few litres of water).

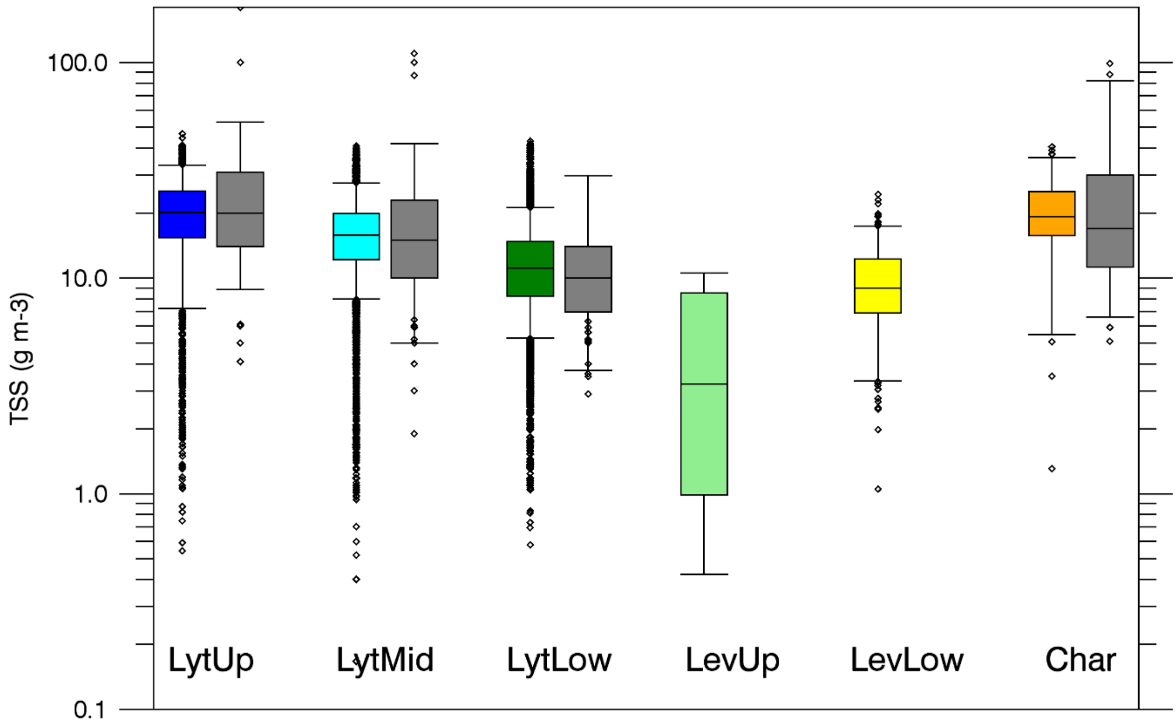


Figure 4-7: Regional comparison of statistical distributions of TSS derived from satellite data and *in situ* sampling. Box-whisker plots (5th, 25th, median, 75th 95th percentile) are given for the six sub-regions. Satellite estimates are shown in coloured boxes: Lyttelton Harbour upper ("LytUp", blue); Lyttelton Harbour middle ("LytMid", cyan); Lyttelton Harbour lower ("LytLow", green); Port Levy upper ("LevyUp", light green); Port Levy lower ("LevyLow", yellow); Charteris Bay ("Char", orange). Satellite data are shown on the left and (where available), *in situ* data (Environment Canterbury sampling) are shown on the right of the pair (grey boxes). There were no Environment Canterbury data in Port Levy (for LevUp and LevLow). Data outside the 5th and 95th percentiles are shown as diamonds.

4.5 Time series analysis

All valid TSS data from each sub-region were extracted for each satellite data overpass and medians calculated (Figure 4-8, Figure 4-9). Satellite data coverage is good for middle and lower Lyttelton Harbour. The amount of satellite data is reasonable for Lyttelton Harbour upper and Port Levy lower, but poor for Charteris Bay. Very few valid satellite observations of Port Levy upper were available and the very few data are not shown here.

To investigate long-term trends, for each pixel in the region a linear trend was fitted to the log of TSS estimated from the QAA algorithm (equation 3) over the 11+ years of MODIS-Aqua acquisition. The significance of the fit was assessed by testing whether the slope was significantly different from zero using a 2-tailed t-test with the degrees of freedom depending on the number of points available at each pixel. The probability of rejecting the null hypothesis that the slope is not significantly different from zero is shown in Figure 4-10. Only at three pixels in the Lyttelton Harbour region was the slope of the regression found to be significantly different from zero at the 1% confidence level. This means that there was little indication in the satellite data that TSS in Lyttelton Harbour was trending (either up or down) over the period of study (July 2002 to April 2014).

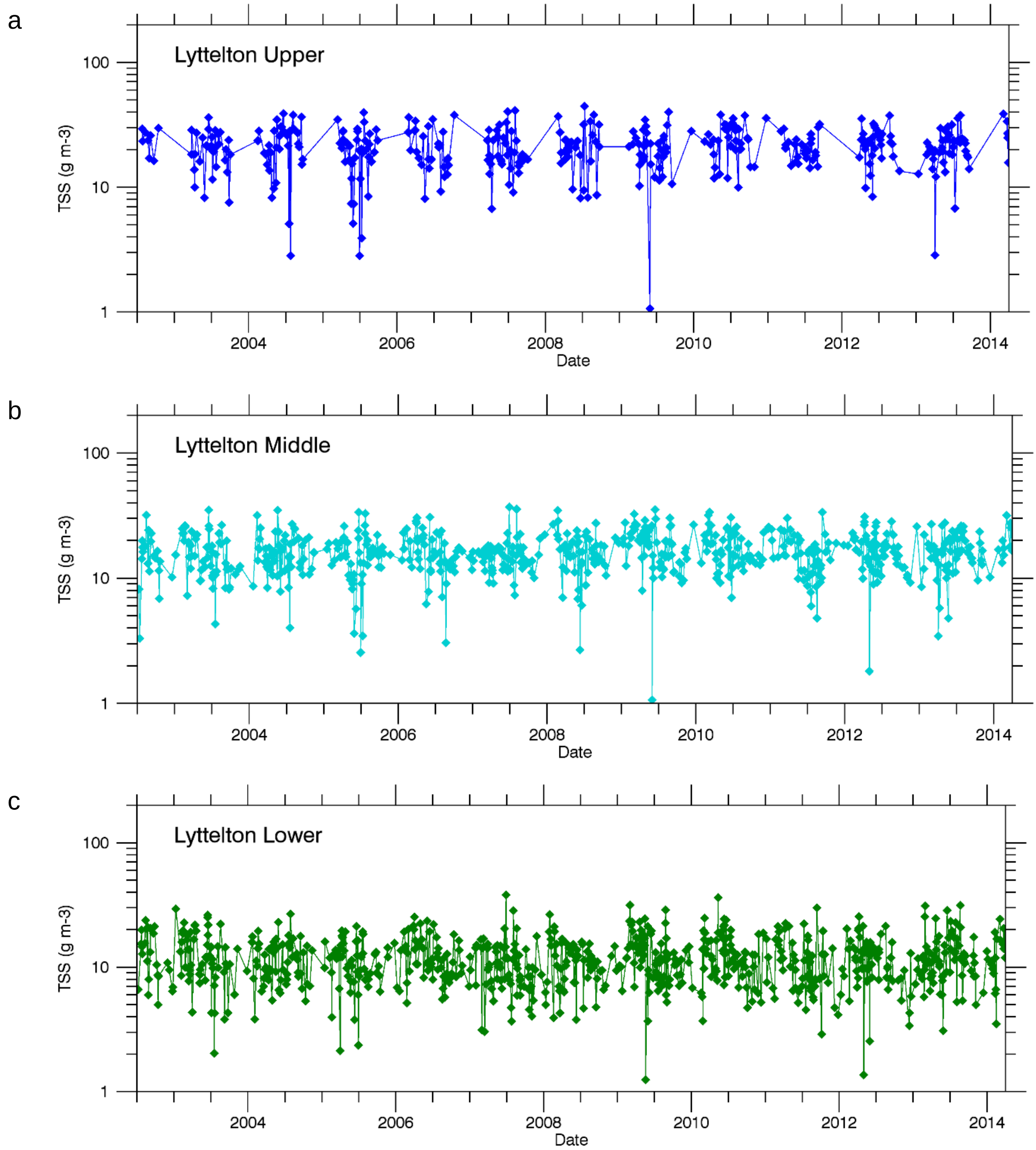


Figure 4-8: Time series of TSS derived from satellite data for Lyttelton Harbour. The median values from each sub-region and each satellite data file are shown: a: Upper Lyttelton Harbour; b: Middle Lyttelton Harbour; c: Lower Lyttelton Harbour.

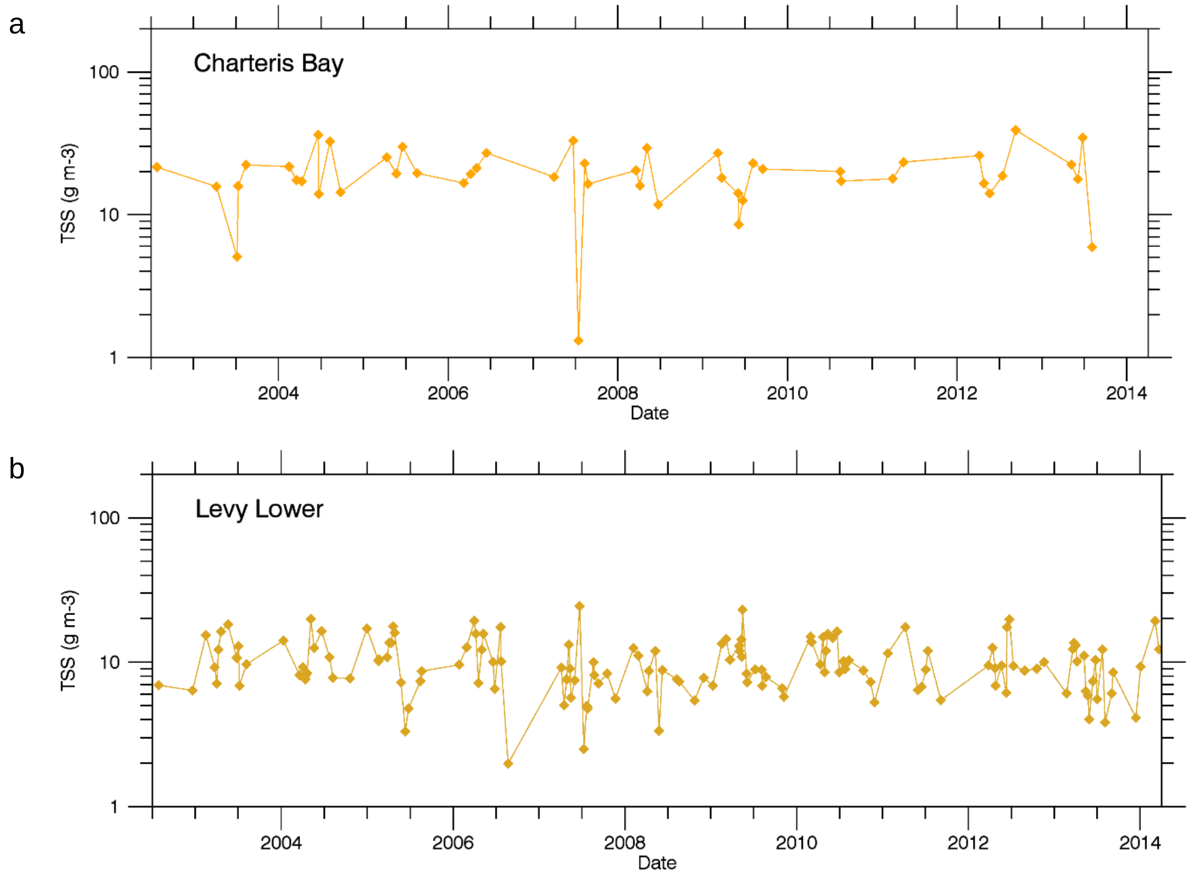


Figure 4-9: Time series of TSS derived from satellite data for Charteris Bay and Port Levy. The median values from each sub-region and each satellite data file are shown: a: Charteris Bay; b: Lower Port Levy.

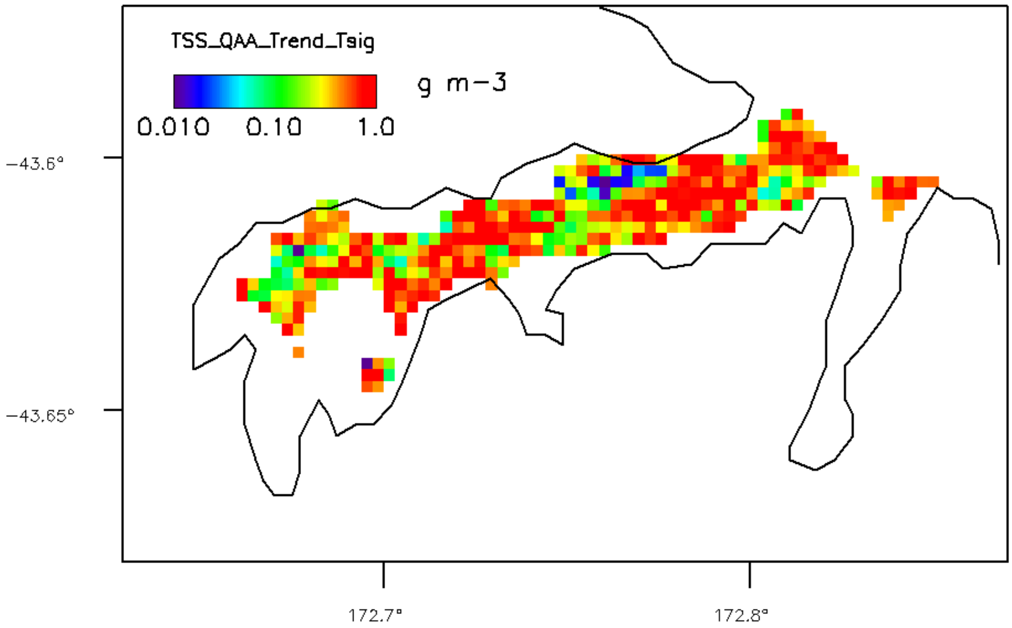


Figure 4-10: Trends in TSS in the satellite dataset over the period July 2002 to April 2014. A linear trend was fitted to the log of total suspended solids estimated from the TSS_QAA algorithm (equation 3) over the 11+ years of MODIS-Aqua acquisition. The significance of the fit was calculated using a two-tailed t-test. The probabilities that the data came from a distribution with zero trend are shown; high values indicate no significant trend detected. There were 3 points with a statistically significant trend at the 1% confidence level and 14 points out of 385 with a statistically significant trend at the 5% confidence level.

4.6 Variation in TSS with distance along estuary

The variation in TSS with distance along Lyttelton Harbour from satellite measurements and *in situ* sampling agree well (Figure 4-11). Total suspended solid concentration is higher upstream (towards the head of Lyttelton Harbour) and lower towards the mouth – consistent with (mostly) land-derived fine sediment mixing progressively with relatively clear seawater along the length of the Harbour. The median concentration at a distance (*lytDist*) of 2.5 km in the satellite data was 21 g m^{-3} and at a distance of 15.5 km (mouth) was 9.3 g m^{-3}. Concentrations of satellite-derived TSS were generally high (> 5 g m^{-3}) through most of the estuary for most of the time. For a given distance along Lyttelton Harbour, the variation between the 5th and 95th percentiles of TSS derived from the satellite data was a factor of ~3.6, with the 5th percentile about 50% of the median (24–55%) and the 95th percentile about 180% of the median (155–210%).

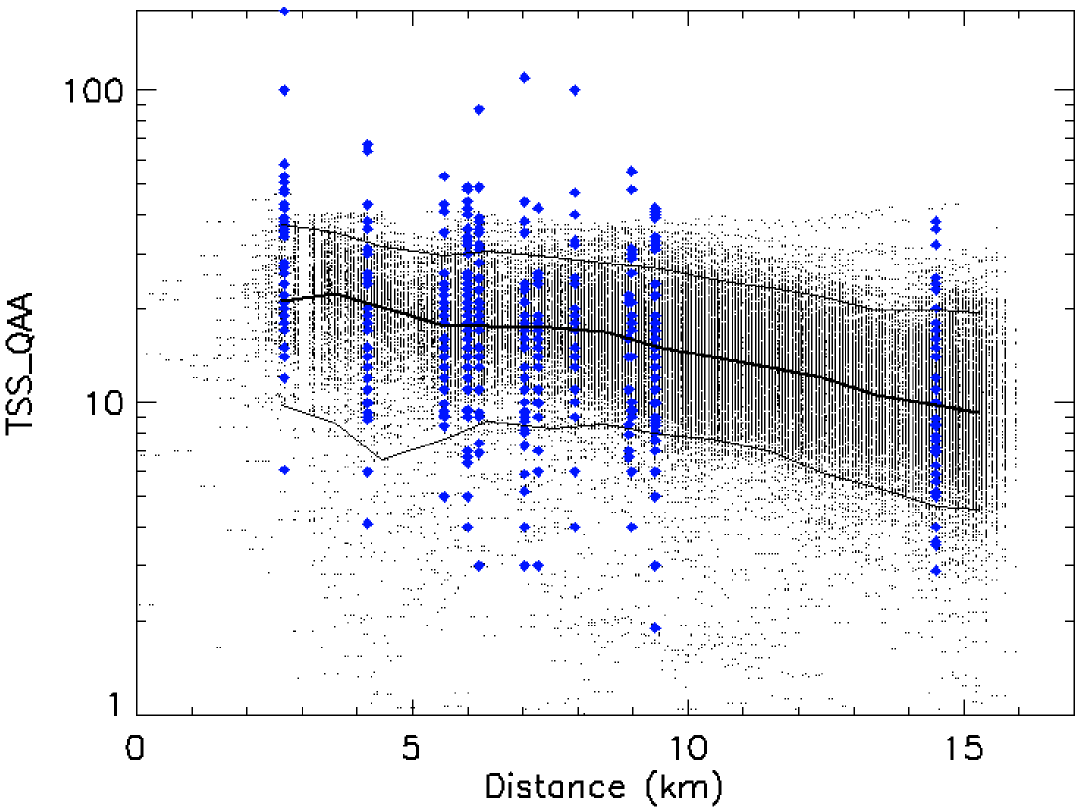
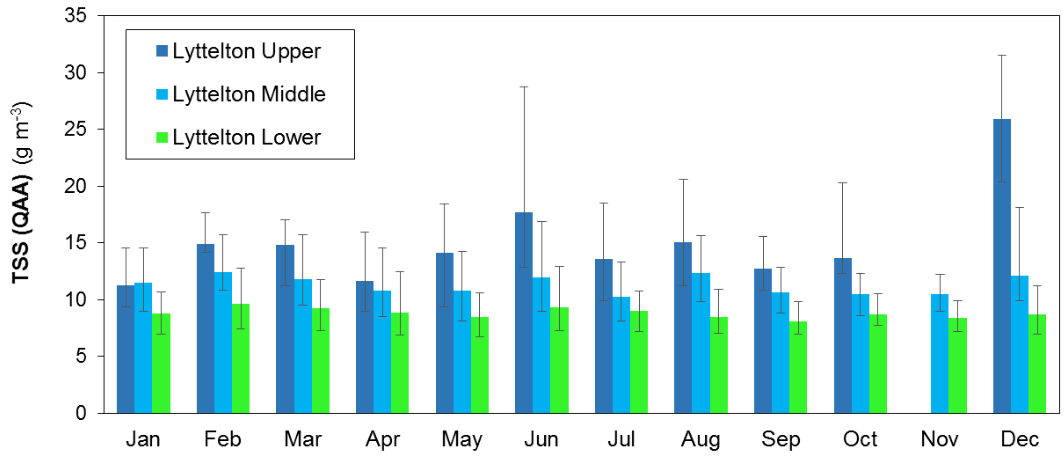


Figure 4-11:Variation in TSS with distance along Lyttelton Harbour. All total suspended solids (TSS, g m^{-3}) estimated using the TSS_GSM algorithm (equation 1) are shown as black dots (n=57,805) against distance along Lyttelton Harbour (km, *lytDist*). The lines indicate (from top) the 95^{th}, 50^{th} and 5^{th} percentiles of the satellite TSS. *In situ* measurements of TSS from Environment Canterbury sampling using boat/helicopter in Lyttelton Harbour are shown against the same distance metric as blue diamonds (n=476).

4.7 Seasonal variation

No clear seasonal pattern is obvious in the satellite SST data in any of the 6 sub-regions considered in this study (Figure 4-12). This implies that day-to-day variation in TSS due to storm-flow inputs and resuspension events probably dominate over expected seasonality in fine sediment inflows from land sources.

a



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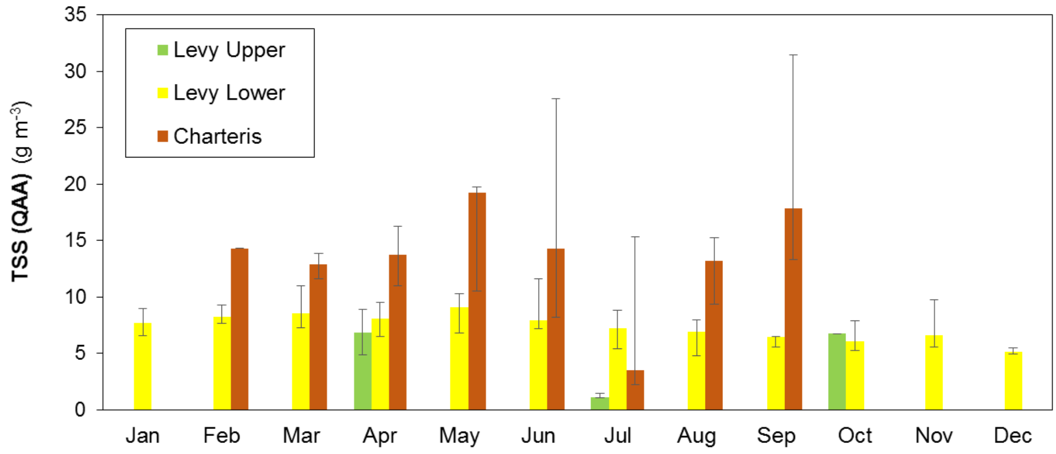

Figure 4-12:Seasonal variation in satellite TSS in descriptive sub-regions. The main coloured bars show median values in the given month and the error bars indicate upper and lower quartiles. a: Lyttelton Harbour main channel; b: Port Levy and Charteris Bay. The absence of bars indicates there were no satellite data in that region in that month.

5 Discussion

Satellite ocean colour remote sensing has the potential to provide frequent, spatially-extensive, long-term information on coloured material in the coastal zone. Concentrations of suspended sediment, phytoplankton and absorption by CDOM/gilvin can potentially be obtained at rates of up to once daily at resolutions of up to 250 m x 250 m. The fact that base data, ongoing calibration and satellite data processing methods are freely available from NASA/NOAA in the US, makes this a potentially cost-effective technology for assisting with coastal management in New Zealand. It is likely that similar observational capability will continue in the medium to long term (decades hence) so this observational technology could be used for long-term detection and monitoring of change. Other potential uses of satellite observations of TSS include characterization of the base-state of suspended sediment in a region, including investigating questions such as to what extent TSS in Lyttelton Harbour are related to river flow, local processes or Pegasus Bay-inflow dynamics. Satellite data can also potentially help in developing and validating hydrodynamic models.

However, obtaining useful measurements of TSS from remote sensing methods is not simple nor are the data without issues. Satellite data are not available under cloudy conditions. Processing methods can fail because of poorly characterized optical properties of aerosols or water constituents. The accuracy of satellite algorithms (which estimate concentrations of material in the water from spectra of ocean colour) can vary regionally. The advent of semi-analytical algorithms for processing ocean colour satellite data has improved the robustness of estimates of water constituents. Semi-empirical algorithms relate the ocean colour to the inherent optical properties (IOPs) of the water constituents. Although empirical components are still required, these relationships are more stable in space and time than band-ratio algorithms. The second step – estimating water constituent concentrations from retrieved IOPs – is highly variable regionally, and local biogeo-optical data are needed. Satellite observations and *in situ* observations (from vessels and moorings) are therefore complementary and an *integrated* approach to monitoring coastal waters will generally be most useful. In this study we used *in situ* measurements from Environment Canterbury and from the NIWA core project based on the NRWQN to develop local algorithms relating satellite-derived particulate backscatter to TSS. This algorithm was non-linear and is specific to the Lyttelton Harbour region.

Developing algorithms using paired empirical measurements is not likely to be useful in the coastal zone for a number of reasons. First, because the majority of the New Zealand coastal zone is obscured by cloud on most days, a large amount of sampling is needed to build up sufficient data for statistically robust analysis. Second, conditions in the coastal zone can be highly variable over short periods (and spatial gradients in water quality are often steep), so that sampling close to the time of the satellite overpass is required; 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) where changes over short periods can substantially affect the optical properties at a given point. In this study, from an Environment Canterbury *in situ* dataset of 721 measurements, there were only 20 match-ups with satellite data on the same day, and even these were usually separated in time by a number of hours. We found that the satellite data in the match-ups were not statistically different from the *in situ* measurements. An alternative indicator of the quantitative reliability of the satellite TSS data was given by the similarity in the satellite-derived and *in situ* measurements of TSS with distance along the centre of Lyttelton Harbour (Figure 4-11), and between different sub-regions (Figure 4-7).

Differences are to be expected in direct comparisons between satellite-derived TSS and *in situ* samples because of the different scales of the observations: 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 litre of water. Small scale variability will hence affect end-to-end match-ups. 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.

Finally, two separate kinds of processing are 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. It is better to use *in situ* sampling to characterise the inherent optical properties of the water constituents, use an analytical or semi-analytical algorithm to use the radiometric satellite measurements to estimate these IOPs, and then apply a local conversion to parameters of interest, like TSS. This approach was used in the present study seemed to be effective.

It has been argued that visual clarity (beam attenuation or secchi depth) is a better quantity than TSS to use for investigating the ecological state of coastal waters (e.g. see Davies-Colley et al., 2014). TSS tends to be more expensive to measure than visual clarity. Also, the beam attenuation coefficient is likely to be better related to ocean colour imagery than TSS. Visual clarity can also be locally calibrated to TSS if desired. Optical clarity may be more ecologically meaningful because fine sediment carries pollutants and is more likely to affect ecology and human use of estuaries than coarse sediment. Fine sediment affects light attenuation more than coarse sediment, but the latter tends to dominate the mass effect (and hence TSS) (Davies-Colley et al., 2014). In situ measurement of TSS also tends to be expensive, discontinuous, slow and not very precise compared to *in situ* optical measurements (Davies-Colley et al., 2014).

Ocean colour satellite data are not usually applicable to water bodies as small as Lyttelton Harbour. With a best resolution of 250 m, the satellite data can only resolve the centre of the estuary. We found that no valid data were obtained within about a km of the coast. Shallow waters at the head of Lyttelton Harbour were also poorly observed by the satellite data. When water is very shallow (less than a few metres) it is possible for ocean colour satellites to ‘see’ the sea-bed through the overlying water. That is, the bed reflection ‘contaminates’ the water backscattering signal. In this case, the in-water algorithm is likely to fail. 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.

Ocean colour satellite data are not obtained when clouds are present, and this is the case for much of the time in the study region. Failure of the MODIS turbid water atmospheric scheme (Wang & Shi, 2007) and semi-analytical algorithm (QAA) also occurred, leading to no data being available. 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 this potential bias in satellite observations (e.g. an optically-instrumented mooring situated in the middle of Lyttelton Harbour).

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. There was a high rate of failure of the NASA turbid-water atmospheric correction algorithm near the coast in the study region. Research is underway at NIWA (and elsewhere internationally) to develop more robust atmospheric correction procedures for ocean colour data over turbid coastal waters (Pinkerton & Wood, unpublished data). If and when such methods become available, it would be useful to reprocess the MODIS-Aqua data archive and regenerate the climatologies of TSS in the study region. In the meantime, having developed this dataset, further summaries and specific analyses may be carried out as required.

6 Conclusions

The main findings of this work are given below.

1. *In situ* measurements from Environment Canterbury and from a NIWA research project based on the NRWQN were used to develop local algorithms to estimate TSS from satellite images. This algorithm was non-linear and is specific to the Lyttelton Harbour region. Satellite-derived TSS data were generated at a 250 m spatial resolution and mapped onto a grid encompassing the Lyttelton Harbour / Pegasus Bay region. Data from MODIS-Aqua between July 2002 and April 2014 were available.

2. Although ocean colour satellite remote-sensing is not usually applied to small water bodies, this study has showed that MODIS-Aqua data can be a powerful method 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 mismatch in time of sampling and satellite imagery among other issues),. Ocean colour satellite observations of TSS are complementary to *in situ* observations (from vessels and moorings) and are likely to be useful in an integrated approach to monitoring coastal waters.

3. The satellite-derived TSS generally decreased with distance along Lyttelton Harbour towards the mouth. Long-term median TSS was estimated as 21 g m^{-3} decreasing to 9.3 g m^{-3} near the mouth of Lyttelton Harbour. The lower reaches of Port Levy had TSS similar to those at the mouth of Lyttelton Harbour (median ~ 9 g m^{-3}). Charteris Bay had median TSS similar to the upper reaches of the Lyttelton Harbour main channel (~ 20 g m^{-3}).

4. Although there was high variability in TSS at a given location between days, satellite-derived TSS were generally high (> 5 g m^{-3}) through most of Lyttelton Harbour estuary for most of the time. For a given distance along Lyttelton Harbour, the 5–95th percentile variation in TSS derived from the satellite data was a factor of 3.6, with the 5th percentile about 50% of the median (24–55%) and the 95th percentile about 180% of the median (155–210%).

5. There is no indication in the satellite data that TSS in Lyttelton Harbour is either increasing or decreasing over the period of study (July 2002 to April 2014).

7 Recommendations

The main recommendations from this study are given below.

1. To improve comparisons between TSS measured *in situ* and by satellites: (a) match water sampling to cloud free conditions; (b) sample close to the centre of the Lyttelton Harbour channel in deep water; (c) sample close to the time of satellite overpass (around 1330 local solar time for MODIS Aqua); (d) carry out sampling in Port Levy.

2. Field sampling which complements satellite remote-sensing could include: (a) shore based sampling which provides information on TSS in areas of Lyttelton Harbour that the satellite cannot see; (b) sampling in shallow water where the satellite images are contaminated by the sea-bed being visible; and (c) an optical mooring in Lyttelton Harbour which would reduce bias in satellite data caused by covariance between TSS and cloud cover.

3. We recommend that Environment Canterbury consider whether more focus on measuring optical attributes *in situ* would be useful instead of, or as well as, TSS. Secchi depth and turbidity are already measured and should be continued. 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). As well as being estimated more accurately by satellite sensors than TSS, optical parameters like water clarity may relate more closely to ecological and human-use impacts of fine suspended matter.

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