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Satellite ocean-colour remote sensing of the Hauraki Gulf Marine Park

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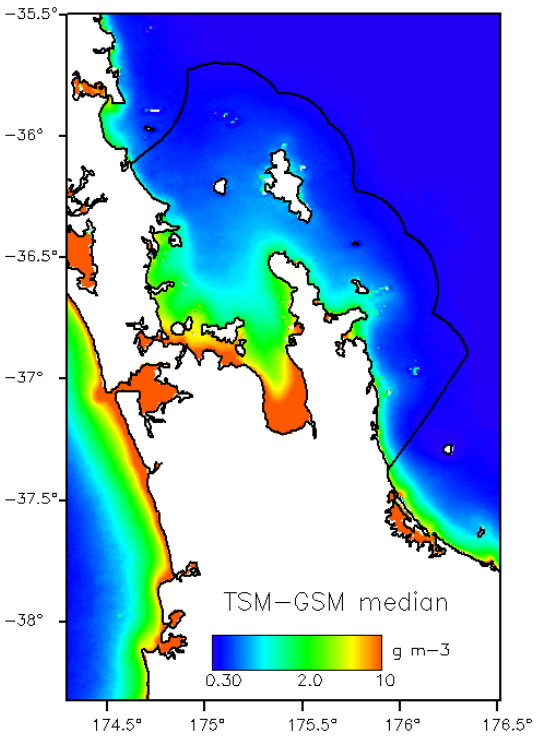

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Cover: Long-term median total suspended matter concentration from the MODIS-Aqua archive derived in this study.

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Executive summary

Waikato Regional Council seeks to use satellite remote sensing methods to provide spatial data on ocean colour to help management of the Hauraki Gulf region. Coastal waters exhibit high natural variability in their characteristic properties, both spatially and seasonally. Observations of the ocean from optical sensors on satellites can complement measurements of water properties from boats and moorings and provide synoptic distributions of these properties over large areas, at daily and longer timescales.

Local (regional) validation and tuning of processing methods is required to use satellite observations. In-water measurements of total suspended matter (TSM) and chlorophyll-a (chl-a) concentration (a proxy for phytoplankton biomass) in the Hauraki Gulf region were assembled to assess and develop “locally-tuned” satellite processing methods. These locally-tuned algorithms were applied to more than a decade of satellite observations from the NASA MODIS-Aqua sensor in order to assess typical conditions and characterise variability of water constituents. The main findings of this work are:

1. Comparison of satellite data with *in situ* measurements led to TSM in the study area being estimated via a scaling of the Garver-Siegel-Maritorena (GSM) semi-analytical algorithm estimate of particulate backscatter at 555 nm (TSM-GSM). The product explained 33% of the variance in the *in situ* TSM data set (N=428). This is comparable with results in similar studies elsewhere.

2. Comparison of satellite data with *in situ* measurements led to chl-a in the study area being estimated via a scaling of the GSM algorithm estimate of phytoplankton absorption at 488 nm (CHL-GSM). The product explained 44% of the variance in the *in situ* chl-a data set (N=138). This is comparable with results in similar studies elsewhere. Co-occurring suspended sediment had little effect on the CHL-GSM product.

3. The TSM-GSM and CHL-GSM satellite products were generated at 500 m resolution for the region encompassing the Hauraki Gulf Marine Park for nearly 11 years (4 July 2002 to 13 June 2013). Long term median, 95th percentiles and 5th percentiles for both products were extracted from the satellite dataset.

4. The long-term satellite composites show higher concentrations of TSM and chl-a inshore, and relatively high concentrations in the Firth of Thames. The spatial distribution of chl-a is similar to that derived from *in situ* measurements alone, but long-term median concentrations of chl-a in inshore regions are higher in the satellite data set.

5. Having developed this dataset, further summaries and analyses may be developed relatively quickly as required.

1 Introduction

1.1 Background

Waikato Regional Council (WRC) seeks to use ocean colour satellite remote sensing methods to provide spatial data to help management of the Hauraki Gulf region (Figure 1-1). Spatial planning in the Hauraki Gulf underpins effective management which balances the requirements of different stakeholder groups, consistent with the Hauraki Gulf Marine Park Act 2000 which aims to better integrate and improve management of the Gulf. The Hauraki Gulf Marine Park Act 2000 emphasises the importance of sustaining the life-supporting capacity of the coastal marine area and islands of the Hauraki Gulf (Hauraki Gulf Forum, 2011).

Because of the dynamic nature of oceanographic and hydrological processes introducing, transporting, transforming and removing coloured material in coastal waters, water sampling from vessels or moorings has limited ability to assess or monitor large-scale patterns (100s of km) over long periods (decades). Satellite ocean colour data can complement *in situ* sampling by observing coloured material in coastal regions on appropriate time and space scales. The main coloured material in coastal waters – phytoplankton, sediment and other non-algal particulate material, and coloured dissolved organic matter (CDOM) – have different optical (absorbing and scattering) properties (Jerlov, 1974; Morel & Prieur, 1977; Mobley, 1994) and hence affect the colour of water in different ways. 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 average seasonal, annual and inter-annual variability in the concentrations of these coloured water constituents to be provided in regions of interest or at site-specific locations.

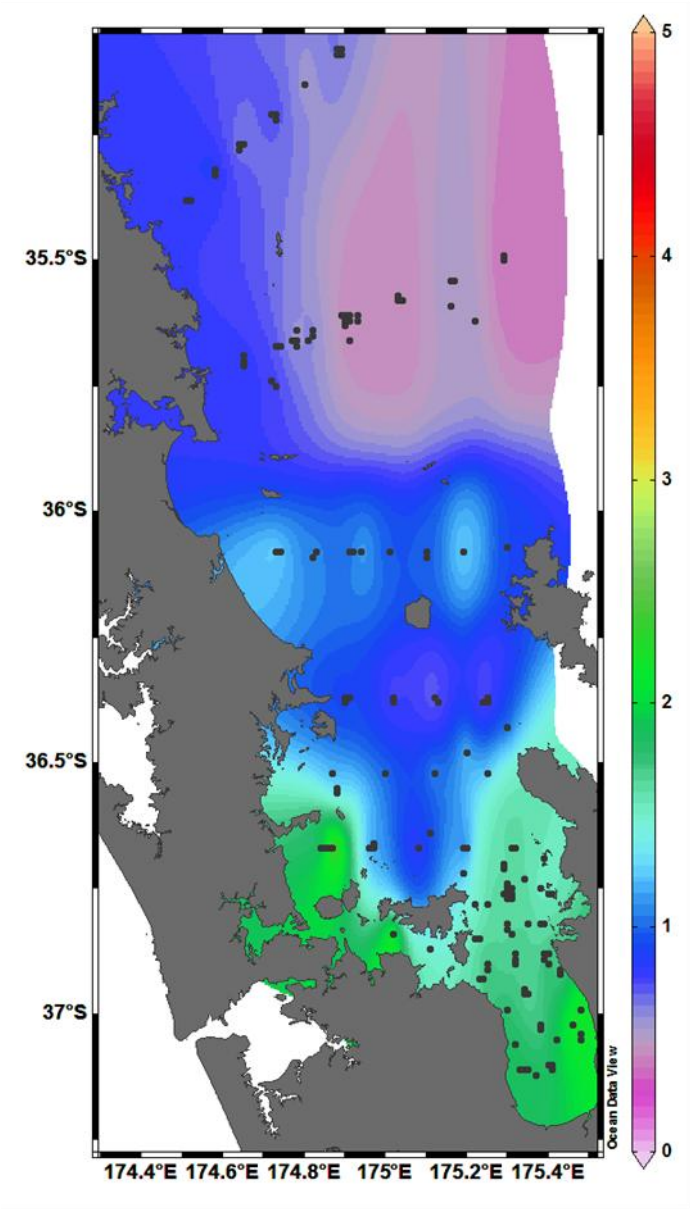

Figure 1-1: Hauraki Gulf study area. Discrete *in situ* sample locations (black circles) between September 1996 and October 2012 from NIWA ocean surveys. The colour scale is contoured chlorophyll-a concentration (mg m^{-3}) from these *in situ* samples averaged over the upper 6 m inshore and upper 15 m offshore (Zeldis et al., 2013).

1.2 Coloured water constituents

What we observe as the colour and clarity of natural waters (apparent optical properties) arise from the inherent optical properties (IOPs, 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). Optically active components are grouped depending on methodological determination: total suspended matter concentration (TSM) encompasses all mass captured by the gravimetric technique; 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) is the remaining colour once all the particulates have been removed by filtering at 0.2 μm. Data from ocean colour satellites is typically used to map coloured material in the surface water in these three categories:

(1) **Total suspended matter (TSM)** – includes all suspended organic and inorganic particulates. 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 (autochthanous) and material brought in from elsewhere (allochthanous). 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 terriginous particulate material includes both refractory (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. Small zooplankton, bacteria and viruses also form part of non-algal particle matter in the water column. Naturally occurring TSM in the region hence contains both organic and inorganic particulates.

(2) **Phytoplankton** - Phytoplankton growth forms algal cells in the upper water column by photosynthesis. Primary production requires the presence of nutrients (principally nitrate and phosphate) brought into surface waters by oceanic processes such as upwelling and mixing, or introduced into the coastal zone by riverine input. 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), which is typically the dominant pigment in terms of absorption, spectral signatures are similar. Therefore, phytoplankton abundance in marine environments is quantified and mapped using the proxy of the concentration of chl-a and measured in units of mg m^{-3}. 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 a complex mixture of humic and fulvic acids formed by the natural breakdown of organic material in soil or aquatic environments. CDOM in the study region will occur from (1) the local breakdown of phytoplankton, zooplankton and other living material; and (2) CDOM of terrigineous origin (allochthanous) introduced to the coastal zone from riverine sources. CDOM from these two sources are generally optically indistinguishable. The shape of the absorption spectrum of CDOM is also typically very similar to that of NAP, being highest in the blue and decreasing to the red end of the visible spectrum.

1.3 Remote sensing of ocean colour

Top-of-atmosphere satellite data must be calibrated and corrected for atmospheric absorption and scattering. About 80–95% of the signal received by a radiometric sensor at the top of the atmosphere is from the atmosphere (Gordon, 1997). In order to obtain the colour of the water, and hence estimate water constituents, it is necessary to remove the contribution from atmospheric scattering. Waters with low concentrations of suspended particulates are black in the near infra-red because of the high absorption by pure water of these wavelengths. Atmospheric correction takes advantage of this fact to estimate the

contribution from the atmosphere. In coastal waters, this method fails because suspended sediments reflect red light out of the water. In oceanic water, it can be assumed that phytoplankton and their associated exudations and breakdown substances are the main drivers of changing water colour, but this is generally not true for coastal waters, where riverine input, resuspension and land erosion introduces sediment and CDOM from elsewhere. Hence, methods that correct for atmospheric radiance at the top of the atmosphere, whilst allowing for non-zero water leaving radiance in the near infra-red, are required for remote sensing in coastal regions (e.g. Lavender et al., 2005; Wang & Shi, 2007).

Although a simple, empirical algorithm relating the blue to green ratio of normalised water leaving radiance to chl-a is accurate to within about 30–40% in open ocean waters at the global scale (O'Reilly et al., 1998), there can be significantly greater uncertainty locally, especially in coastal waters (Pinkerton et al., 2005). Similarly, the accuracy of band ratio algorithms for TSM and other products depend on assumed relationships between IOPs. Semi-analytical algorithms address these issues by de-convolving remotely sensed reflectance spectra simultaneously into contributions by all potential optically active constituents, but still assume typical spectral shapes for the absorption and scattering properties of phytoplankton, dissolved substances and inorganic particulates (Garver & Siegel, 1997; Lee et al., 2002). Variations in the particular IOPs in different regions can lead to errors in ocean colour algorithms. Because it is not possible to determine *a priori* which algorithm performs best in any given region, biogeo-optical data must be collected and used to select and, if necessary, locally tune in-water algorithms.

1.4 Objectives

This study had three 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 the algorithms to the *in situ* data.
2. Assess the distribution and concentrations of TSM over the past decade in the study region. Provide these data to WRC to aid spatial planning and management.
3. Assess the distribution and concentrations of phytoplankton biomass via the proxy of near-surface chl-a concentration over the past decade in the study region. Provide these data to WRC to aid spatial planning and management.

1.5 Structure of report

Section 2 details satellite measurement methods, presents a brief summary of 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. Sections 3 and 4 present satellite ocean colour observations for the two products of objectives 2–3, namely TSM and chl-a. Satellite data are 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 4 discusses and briefly summarises the results. Appendix A shows the number of valid pixels used in the climatological satellite data analysis.

2 Objective 1: Evaluation of satellite products

2.1 Source of satellite data

All ocean colour satellite data 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). Level 1A (top of atmosphere, calibrated) MODIS-Aqua imagery was acquired from the Ocean Biology Processing Group at NASA (before mid-2007) and from the NIWA direct-broadcast X-band receiver (since mid-2007). MODIS-Aqua data were available from the start of operation (4 July 2002) to 13 June 2013 (nearly 11 years, 3998 days). In total we had 4278 individual data files. 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 the local New Zealand receiver was installed in mid-2007, the data obtained from NASA was split into 5-minute “granules” and typically two granules (and hence 2 files) 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.

2.2 Atmospheric correction

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 (Wang & Shi, 2007). In this study therefore, atmospheric correction was applied using the NIR/SWIR switching algorithm (Wang & Shi, 2007) to maximise sensitivity to small-scale variability in aerosols near-shore. We note that this is an area of active international research and better methods for atmospheric correction over turbid waters may become available in the future.

2.3 Satellite data grid

All parameters were calculated at a pseudo-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 then mapped onto a nominal-500 m resolution grid which had 0.0045° resolution in latitude and 0.0056° resolution in longitude. The centre points of the pixels in the study area were from 174.2952°E to 176.5128° E, and 35.497° S to 38.323° S. This area was selected to cover the Department of Conservation equal-area grid of the region as requested by Waikato Regional Council. The number of pixels in the grid was 397 (x) by 629 (y), with a total number of 249,713 pixels per scene.

2.4 Testing and tuning satellite in-water algorithms

Ocean colour remote sensing of turbid, coastal waters is an evolving field of research in New Zealand and internationally, with many approaches proposed by different researchers. At present, no approach has been demonstrated to be more appropriate than others in all areas. For the purposes of this study, we evaluated the main satellite products relevant to observing total suspended matter and chlorophyll-a concentration which are supported by NASA for MODIS-Aqua processing using an "end-to-end" comparison approach. The evaluation of these alternative algorithms and satellite products are presented in the following sections. The evaluation was carried out as follows: (1) bring together all available *in situ* measurements of near-surface TSM and chl-a in the study region over the last 11 years; (2) select a set of candidate satellite algorithms/products to test; (3) generate all candidate satellite data products for all satellite overpasses of the study area; (4) extract satellite data in a grid of 3x3 pixels around each *in situ* sampling location; (5) compare *in situ* data with extracted satellite data at the location of the *in situ* sampling from the three satellite overpasses that are closest in time to the sampling. Exact day comparisons were not enforced because areas were usually cloud covered so this would lead to too few match-ups for robust validation/tuning. The data were only used for calibration/validation of the satellite data if two conditions were met:

1. the mean time difference between the *in situ* sampling and the 3 closest satellite overpasses with valid data at that point was less than 10 days.

2. the coefficient of variation (CV), defined as the ratio of the standard deviation to the mean of the 3 extracted data points, was less than 0.5.

We chose not to use the *in situ* data to adjust the specific inherent optical properties (IOPs) within semi-analytical algorithms at this time but this is an area of ongoing research at NIWA. The set of candidate processing methods was chosen to include those most likely to deliver useful results. There are a large number of 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). It is likely that algorithms for remote sensing of coastal waters will continue to develop in the future, and it may be worthwhile to revisit the selection of the most promising methods in the future.

2.5 Long-term median, high and low satellite data values

Having chosen the products to use (see below), long-term medians were calculated at each pixel in the study area. Both TSM and chl-a are log-normally distributed in the region and medians provide a better indication of typical conditions than the mean. Indicative high and low satellite data values were calculated for each pixel using the full 11-year time series. "High" was taken as the 95th percentile at each pixel and "low" as the 5th percentile for each pixel. This approach, rather than taking the maximum and minimum values as each pixel, was used to avoid spurious single values giving extremely high or low values which can occur on cloud edges or where the atmospheric correction fails.

2.6 *In situ* data available

In situ data were obtained from NIWA core-funded bio-optical measurements, as described in Zeldis et al. (2013). We requested monitoring data (chl-a, TSM, water clarity) from the Wilson Bay Group A Consortium, but we were not granted permission by the Wilson Bay Group A Consortium to use these data to evaluate the satellite algorithms. It is not known how these additional data would affect the conclusions of the algorithm evaluation. This would be useful to test in the future if possible.

For TSM, a 2 L subsample was placed in an acid washed plastic container and labeled for gravimetric analysis (Strickland & Parsons, 1972). A known volume was filtered onto a pre-weighed 25 mm diameter GF/F (glass fibre filter) and oven drying for total TSM, followed by combustion for the inorganic fraction (TSMi). Volatile, organic suspended matter (TSMo) was determined by difference. Total suspended matter (TSM) concentrations ranged from 0.5–180 g m^{-3}, with a mean value of 4.4 g m^{-3} (N=789).

Chl-a concentration was measured by extracted (in vitro) fluorometric analysis (Strickland & Parsons, 1972) and by high performance liquid chromatography (HPLC). As recommended by NASA in protocols for satellite validation and calibration (Mueller et al., 2002), HPLC data were used where available, otherwise, in vitro fluorometric chl-a data were used. In both cases, water was filtered through a 25mm GF/F noting volume filtered and in subdued light to avoid pigment degradation. Once filtration was complete forceps were used to fold the filter in half, and it was then placed in a labelled cryovial and stored in liquid nitrogen. Pigments were extracted in 90% acetone by probe sonication and separated on a c8 column according to the method of Zapata (2000). Chl-a concentrations measured ranged from 0.1 to 6.6 mg m^{-3} with a mean of 1.3 mg m^{-3} (N=268).

2.7 Satellite algorithms for total suspended matter (TSM)

We tested four candidate satellite products available from which to estimate TSM: (1) band-ratio TSM (Clark, 1997); (2) PIC (particulate inorganic carbon (Balch et al. 2005; Gordon at al. 2001); (3) BBP-QAA (backscatter of particulate material at 488 nm by Quasi-Analytical Algorithm (QAA) update v5, Lee et al., 2002; Lee et al., 2009); and (4) BBP-GSM (backscatter of particulate material at 555 nm by Garver-Siegel-Maritorena (GSM) algorithm, Garver & Siegel 1997; updated processing available from: www.icess.ucsb.edu/OCisD/). Note that because the backscatter spectrum of naturally-occurring particulates is relatively flat in the visible part of the spectrum, difference in the reference wavelength used by the QAA and GSM algorithms is not important. Results are shown in Figure 2-1.

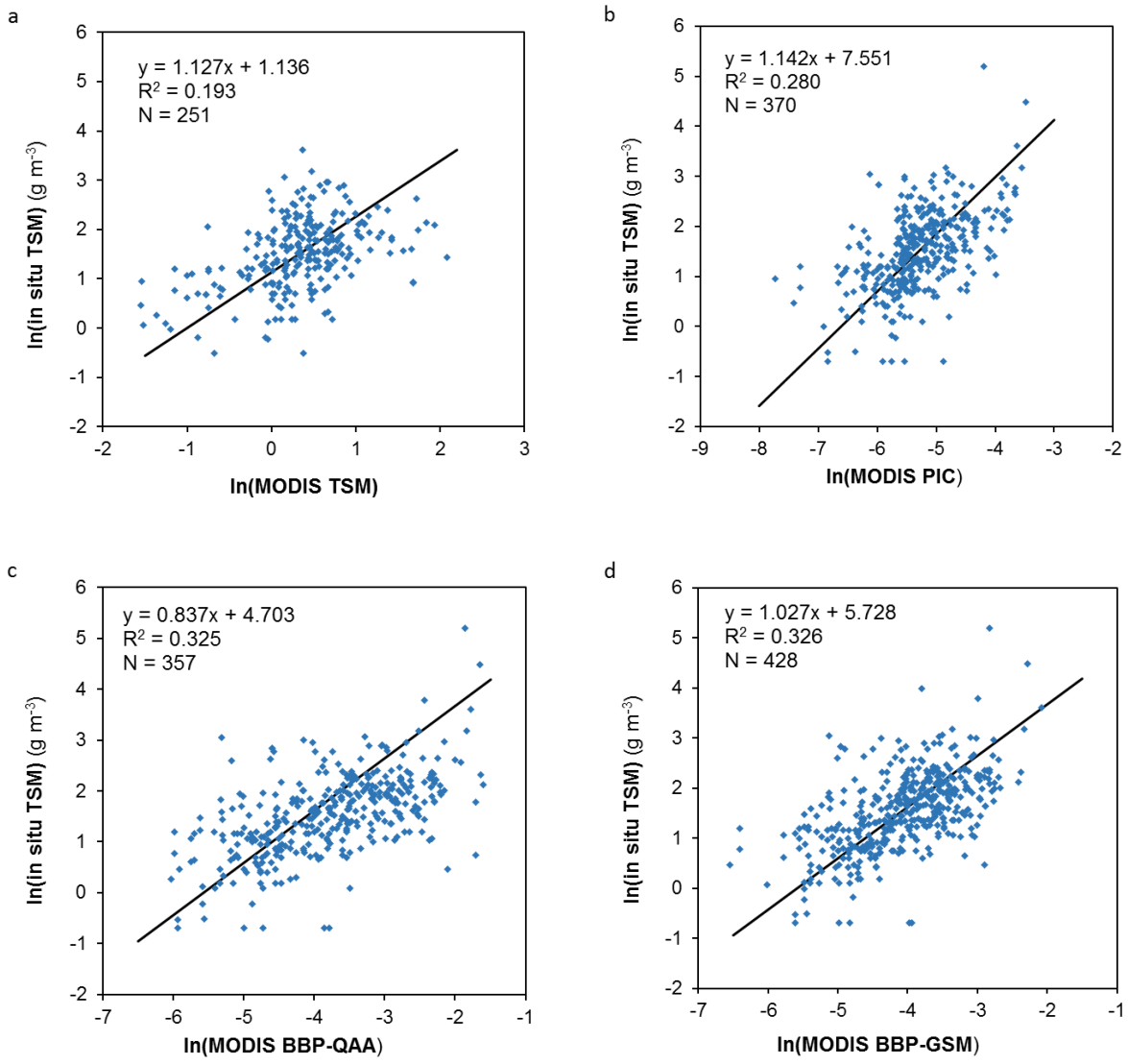

Figure 2-1: Testing algorithms for TSM against *in situ* data. *In situ* measurements of gravimetric total suspended matter ("*in situ* TSM") and four satellite products: (a) MODIS TSM semi-empirical suspended sediment algorithm (g m^{-3}); (b) MODIS particulate inorganic carbon (PIC) (molC m^{-3}); (c) particulate backscatter at 488 nm from the MODIS quasi-analytic algorithm (BBP-QAA) (m^{-1}); (4) particulate backscatter at 555 nm from the MODIS Garver-Siegel-Maritorena algorithm (BBP-GSM) (m^{-1}). Solid lines are least-squares model-2 regression lines, for which equations, coefficients of determination (R^2) and number of points (N) are shown.

For the purposes of this report, we select the scaled BBP-GSM product as being the best candidate for TSM (equation 1). This product explained 33% of the variance in the *in situ* data set on TSM in log-log space (N=428).

$$\text{TSM-GSM} = \exp[1.027\ln(\text{BBP-GSM}) + 5.728] = 307.3\ (\text{BBP-GSM})^{1.027} \quad \text{(equation 1)}$$

Where:

TSM-GSM = modified algorithm for total suspended matter concentration (TSM, g m^{-3}) in the study area

BBP-GSM = MODIS-Aqua particulate backscatter at 555 nm from GSM algorithm (m^{-1})

2.8 Satellite algorithms for chlorophyll-a concentration (chl-a)

There were four satellite products available from which to estimate chl-a concentration (mg m^{-3}): (1) MODIS default band-ratio CHL product (O'Reilly et al., 1998); (2) FLH (fluorescence line height, Letelier & Abbott, 1996); (3) APH-QAA (absorption of phytoplankton at 488 nm using the QAA v5 algorithm, Lee et al., 2002; Lee et al., 2009); (4) APH-GSM (absorption of phytoplankton at 488 nm using the GSM algorithm, Garver & Siegel 1997; updated processing available from: www.icess.ucsb.edu/OCisD/).

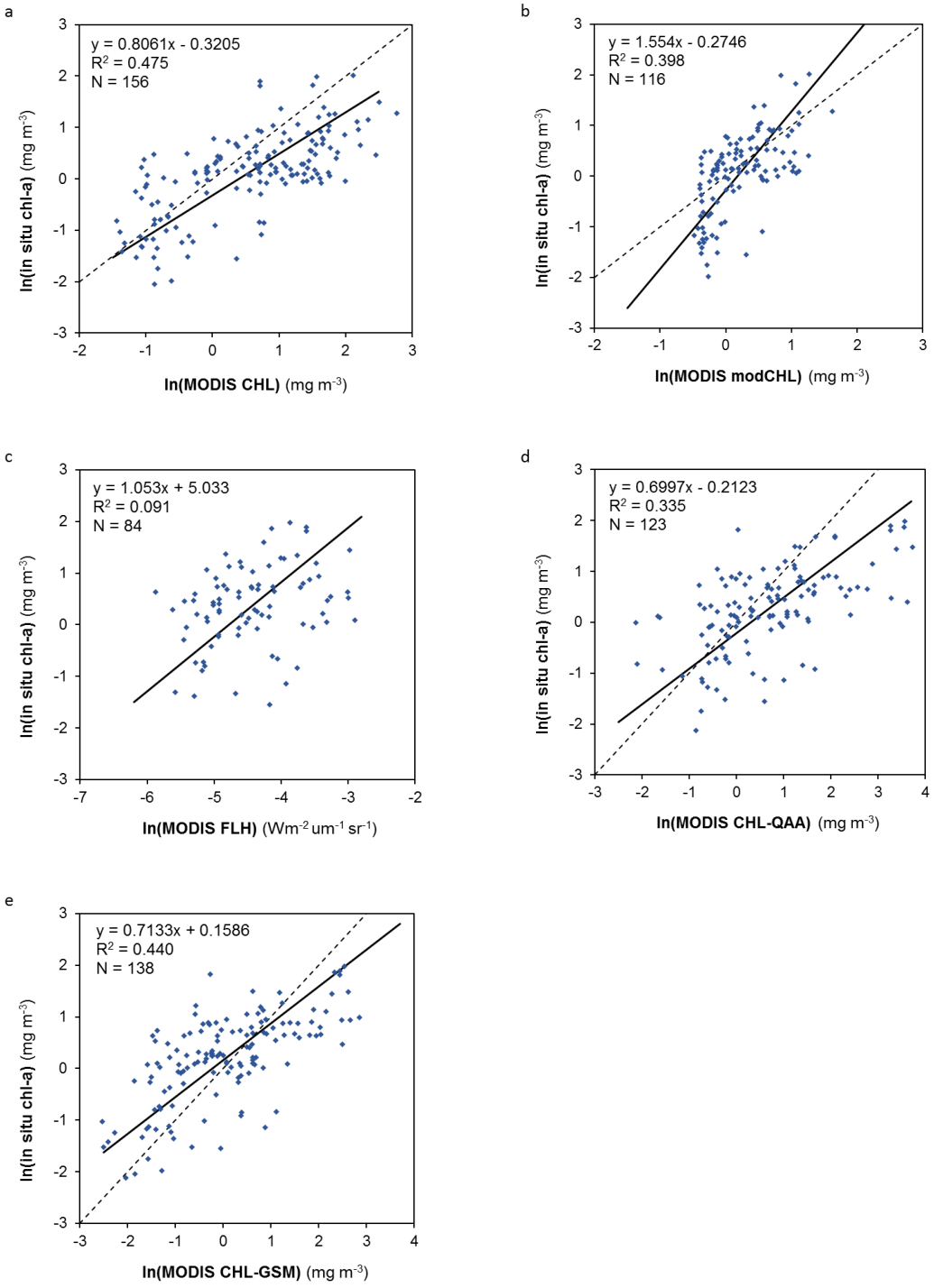

Figure 2-2: Testing algorithms for chl-a against *in situ* data. *In situ* measurements of chl-a ("*in situ* chl-a") and four satellite products: (a) MODIS band ratio chl-a algorithm (CHL, mg m^{-3}); (b) CHL product corrected using MODIS Clark-TSM product (modCHL, mg m^{-3}); (c) MODIS fluorescence line height (FLH, (Wm^{-2} μm^{-1} sr^{-1}); (d) chl-a based on scaling phytoplankton absorption at 488 nm from the MODIS quasi-analytic algorithm (APH-QAA) (m^{-1}) by Bricaud et al. (1995); (e) chl-a by scaling phytoplankton absorption at 488 nm from the MODIS Garver-Siegel-Maritorena algorithm (APH-GSM) (m^{-1}) by Bricaud et al. (1995). Dashed lines are the 1:1 relationship. Solid lines are least-squares model-2 regression lines, for which equations, coefficients of determination (R^2) and number of points (N) are shown.

2.8.1 Band-ratio chl-a algorithm (CHL)

The MODIS band-ratio (semi-empirical) chlorophyll-a product (CHL) product (O'Reilly et al., 1998) explains a reasonable proportion of the variation in *in situ* measurements of chl-a in log-log space (R^2 = 0.48, N=156, Figure 2-2a). However, this correlation is likely to be driven (in part at least) by the fact that sediment and chl-a tend to be positively correlated. Riverine run-off into the coastal zone tends to contain elevated TSM and elevated nutrients which leads to higher concentrations of chl-a. In this study, the differences between the satellite CHL product and *in situ* measurements of chl-a are correlated with the amount of TSM in the water according to the MODIS Clark-TSM product (R^2 = 0.74, data not shown). This is a known and expected property of the algorithm: sediment co-occurring with phytoplankton is misidentified as chl-a by the band-ratio algorithm leading to overestimation. It is possible to correct for the effect of the co-occurring sediment using the MODIS Clark-TSM (Figure 2-2b). This corrected CHL product (called "modCHL") explains 39% of the variance in *in situ* measurements of chl-a in log-log space, and the overestimation is very much reduced (note change of relationship of fitted line and 1:1 line in Figure 2-2a and Figure 2-2b).

2.8.2 Fluorescence line height (FLH)

The MODIS fluorescence line height product (FLH) was derived from a line-height algorithm based on the spectral shape of water-leaving radiance in the red, as determined by solar-stimulated fluorescence emission of chl-a (Letelier & Abbott, 1996). The FLH product is potentially useful for estimating chl-a because chlorophyll natural (sun-stimulated) fluorescence is related to chlorophyll concentration and, unlike products derived using band-ratio algorithms, is unlikely to be affected by co-occuring sediment (Hu et al. 2005; McKibbon et al. 2012). Also, the FLH product is not affected by CDOM loading (Hoge et al., 2003).

Here, the *in situ* data shows that the FLH product explains only a small amount of the variation in *in situ* measurements of chl-a (Figure 2-2c, R^2 = 0.09, N=84). The large residual (unexplained) variability is likely to be due to the variability of the intensity of the incident light combined with variation in the physiological state of the phytoplankton, including nutrient status and phytoplankton functional group. These factors are known to affect the relationship between fluorescence line height and chl-a concentration in other areas of the world (Letelier & Abbott, 1996). We do not have sufficient information to attempt to correct for changes in physiological state of the phytoplankton across the study area.

2.8.3 QAA phytoplankton absorption product (APH-QAA)

Phytoplankton specific absorption typically decreases with increasing absorption by phytoplankton as a result partially of the "package effect": as the concentration of phytoplankton increases, the proportion of the pigment which interacts with a light beam decreases because of self-shading (Bricaud et al. 1995; Bissett et al. 1997). The coefficients for the relationship between chl-a and phytoplankton absorption at 488 nm were taken from Bricaud et al. (1995) and used to estimate chl-a from the APH-QAA product. The scaled APH-QAA product (CHL-QAA) explains a reasonable amount of the variation in measurements of chl-a made *in situ* (R^2 =0.335, N=123, Figure 2-2d).

2.8.4 GSM phytoplankton absorption product (APH-GSM)

As above, the relationship between chl-a and phytoplankton absorption at 488 nm were taken from Bricaud et al. (1995) and used to estimate chl-a from the APH-GSM product (equation 2). The scaled APH-GSM product is called CHL-GSM. This product explains a reasonable amount of the variation in measurements of chl-a made *in situ* in log-log space (R^2 = 0.440, N=138, Figure 2-2e). There is no evidence that the residual between CHL-GSM and *in situ* measurements of chl-a is affected by co-occuring suspended sediment (R^2 = 0.08. data not shown). For the purposes of this report, we select the CHL-GSM product as being the best candidate for chl-a.

$$\text{CHL-GSM} = (\text{APH-GSM} / 0.0279)^{\wedge}(1/(1-0.0279)) \qquad \text{(equation 2)}$$

$$= 290.7\ (\text{APH-GSM})^{1.585}$$

CHL-GSM = chl-a product for the study region (mg m^{-3})
APH-GSM = phytoplankton absorption at 488 nm from the GSM algorithm (m^{-1})

3 Objective 2: Satellite total suspended matter

Averaged over the entire MODIS data 10 year record (2002-2012), TSM was distributed as shown in Figure 3-1 (long-term median), Figure 3-2 (high values, 95th percentiles) and Figure 3-3 (low values, 5th percentiles).

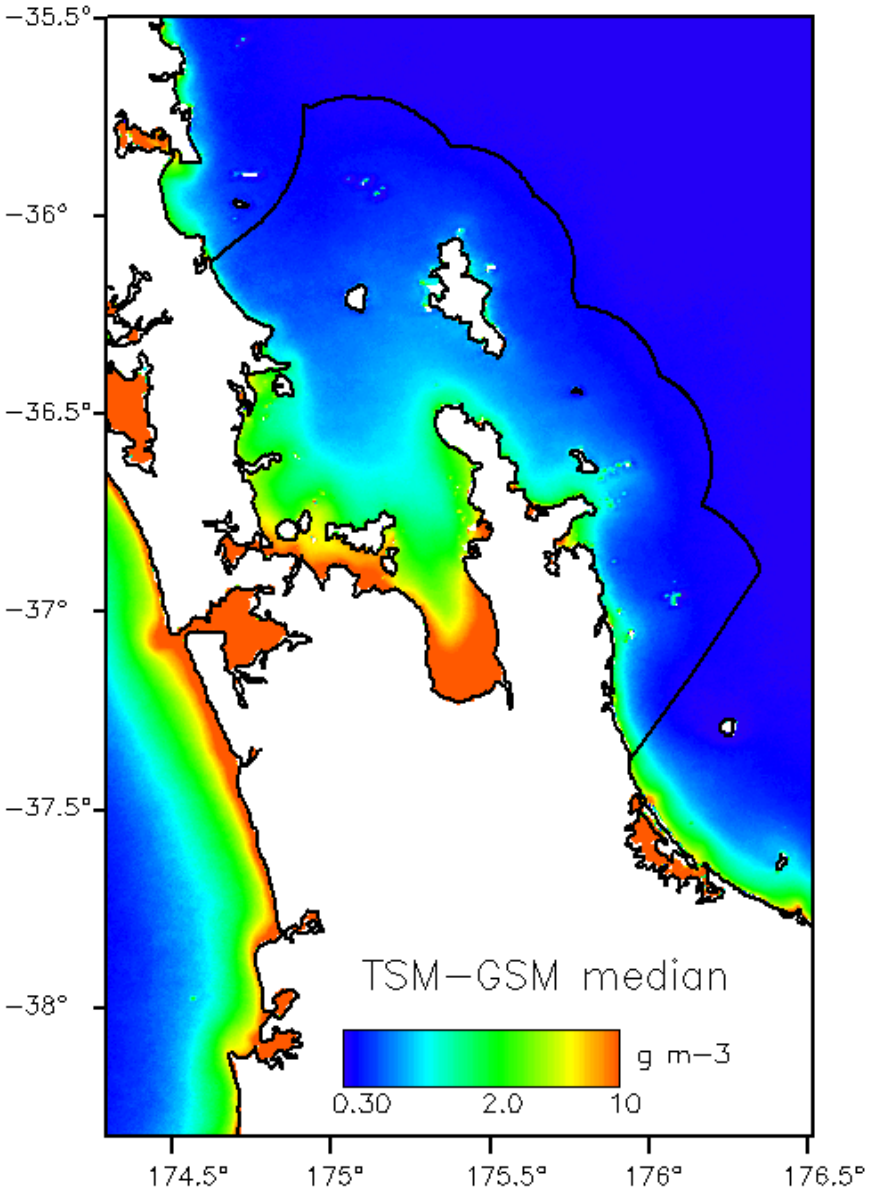

Figure 3-1: Long-term median total suspended matter (TSM). Values calculated using the TSM_GSM algorithm (equation 1). Values were calculated as the median value over 11 years of MODIS-Aqua data in each pixel. Note the logarithmic scale in concentration. The black line indicates the boundary of the Hauraki Gulf Marine Park.

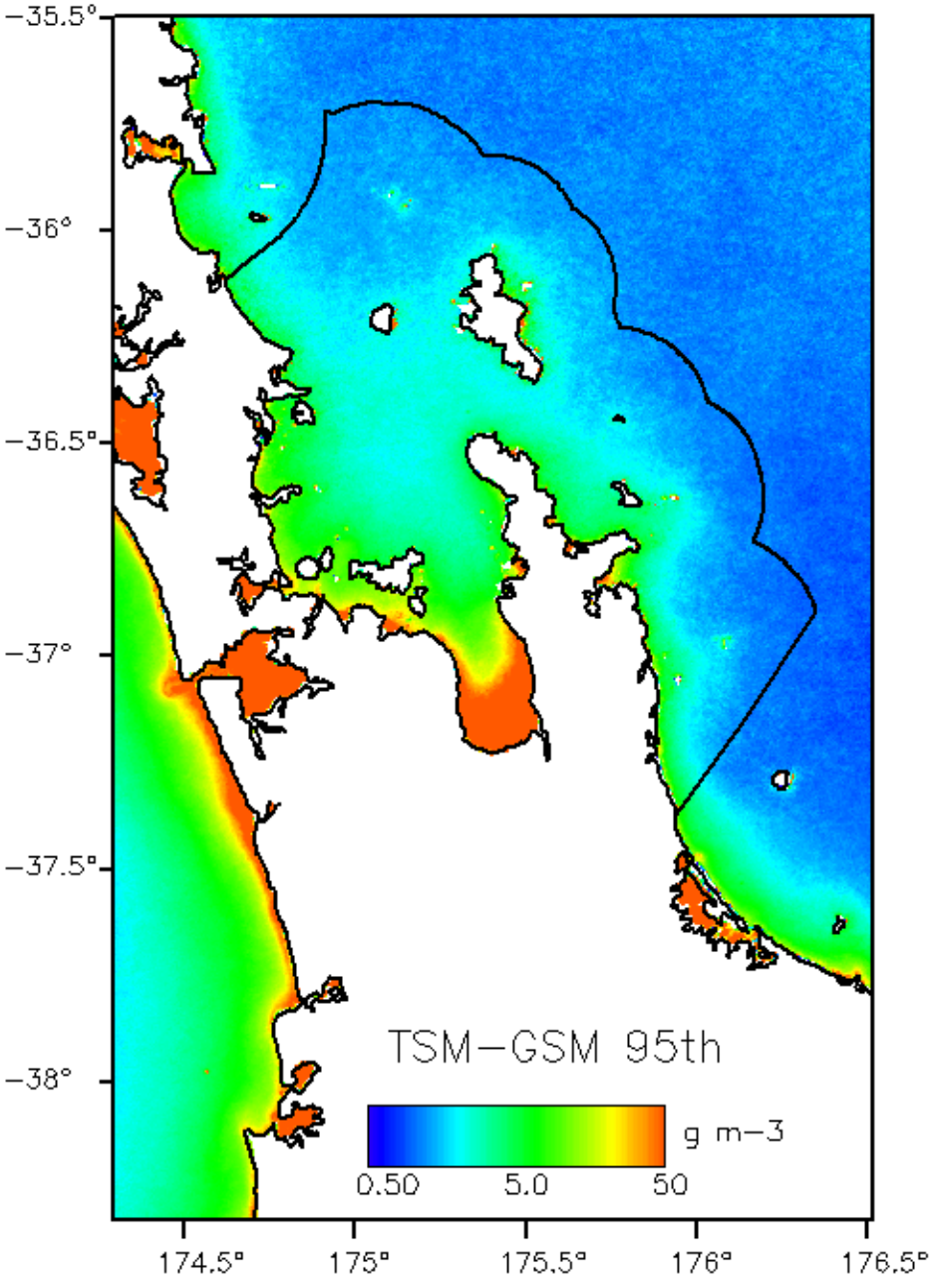

Figure 3-2: 95th percentiles of total suspended matter (TSM). TSM estimated using the TSM-GSM algorithm (equation 1). Values are calculated as the 95th percentile at each pixel over 11 years of MODIS-Aqua data. Note different scale to Figure 3-1 and Figure 3-3. The black line indicates the boundary of the Hauraki Gulf Marine Park.

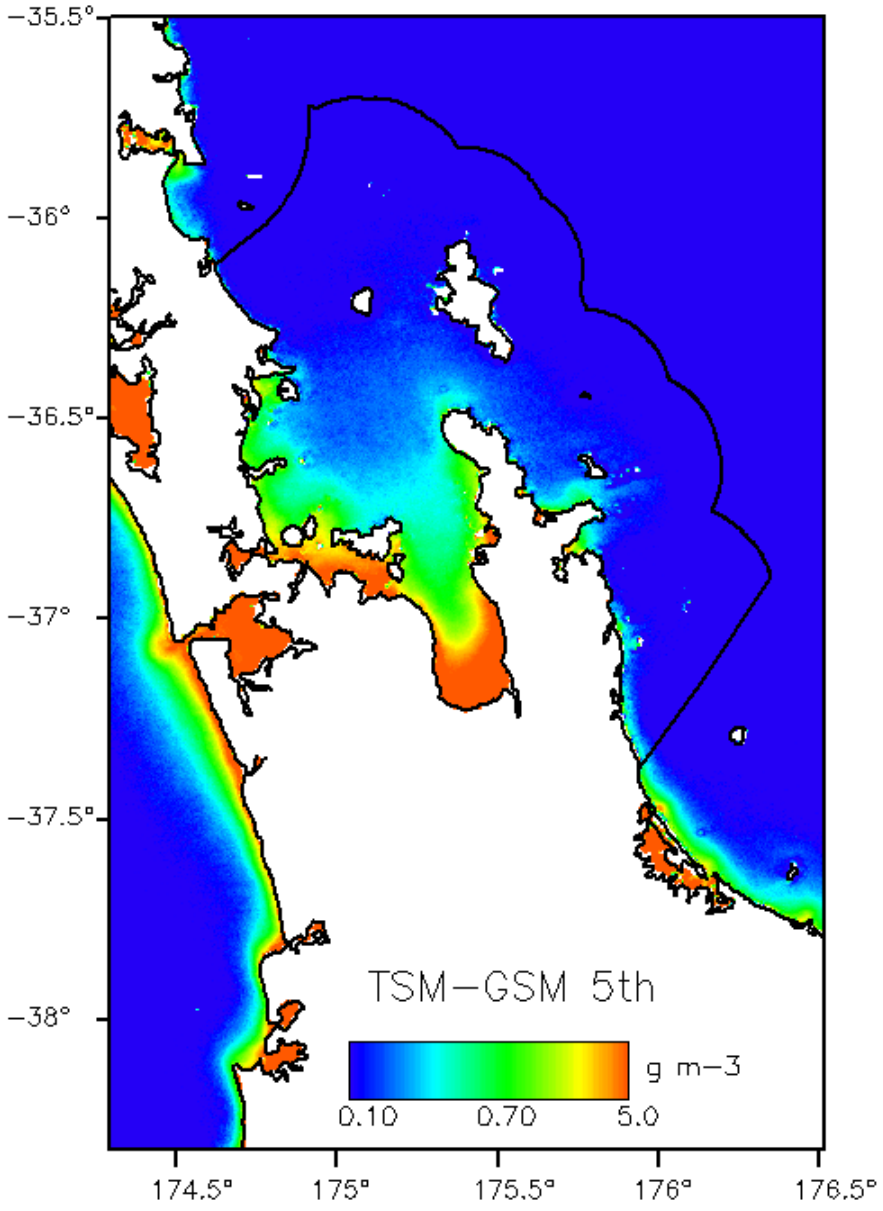

Figure 3-3: 5th percentiles of total suspended matter (TSM). TSM estimated using the TSM_GSM algorithm (equation 1). Values are calculated as the 5th percentile at each pixel over 11 years of MODIS-Aqua data. Note different scale to Figure 3-1 and Figure 3-2. The black line indicates the boundary of the Hauraki Gulf Marine Park.

4 Objective 3: Satellite chlorophyll-a concentration

Averaged over the entire MODIS data 11 year record (2002–2013), chl-a was distributed as shown in Figure 4-1 (long-term median), Figure 4-2 (95th percentiles) and Figure 4-3 (5th percentiles).

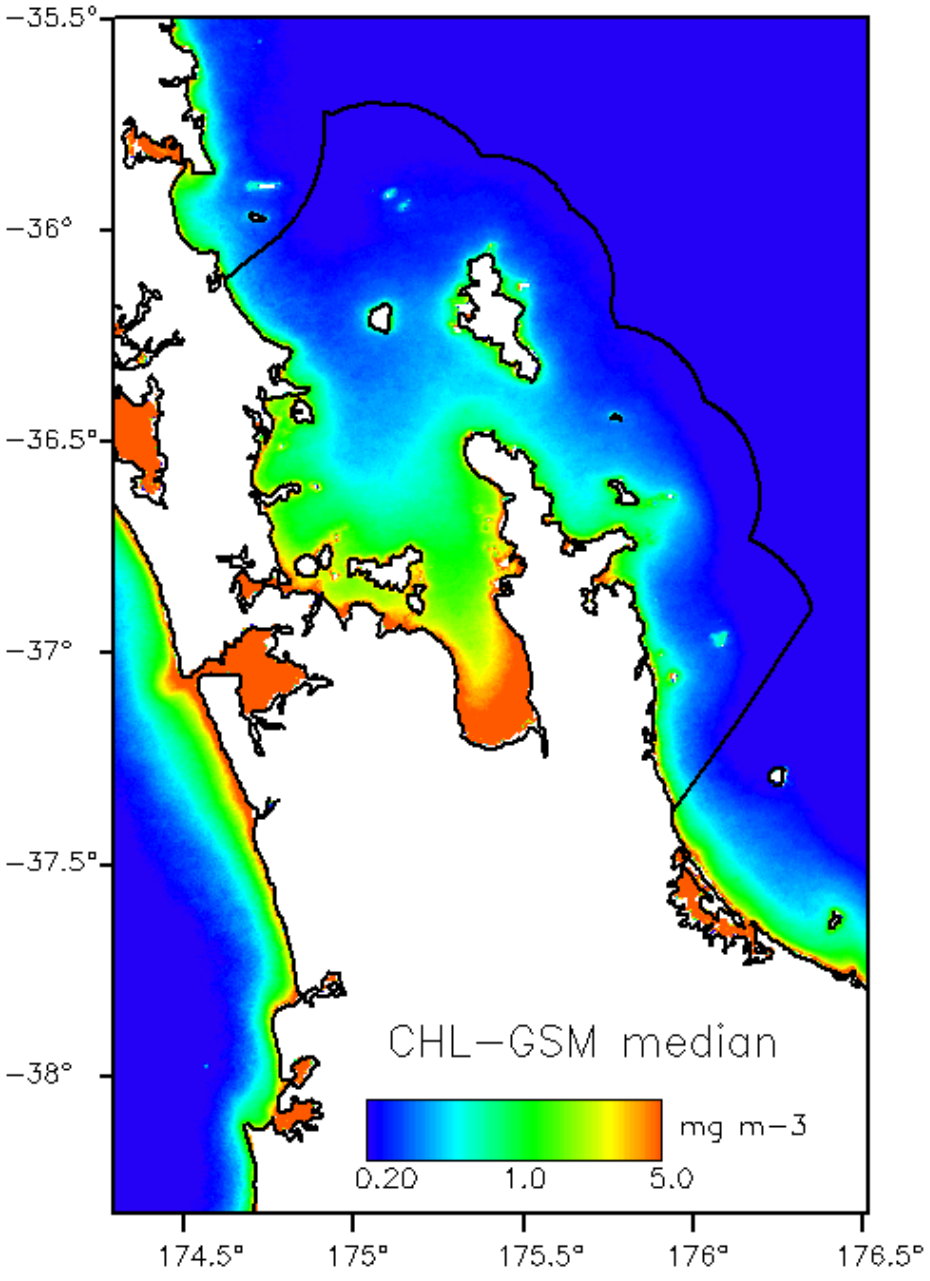

Figure 4-1: Long-term median chlorophyll-a concentration (chl-a). Chl-a estimated using the CHL-GSM algorithm (equation 2). Values were calculated as the median value over 11 years of MODIS-Aqua data in each pixel. Note the logarithmic scale in concentration. The black line indicates the boundary of the Hauraki Gulf Marine Park.

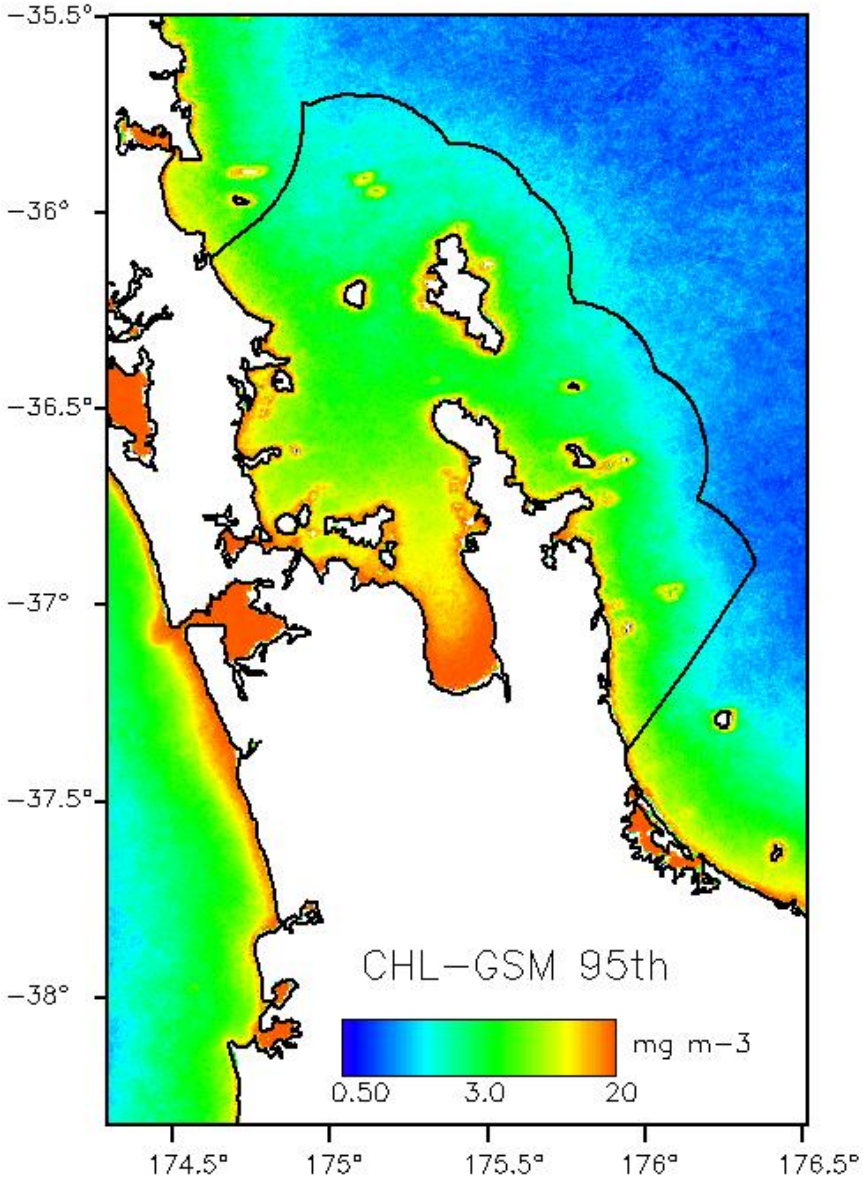

Figure 4-2: 95th percentiles of chlorophyll-a concentration (chl-a). Values obtained from the CHL-GSM algorithm (equation 2). Values are calculated as the 95th percentile at each pixel over 11 years of MODIS-Aqua data. Note different scale to Figure 4-1 and Figure 4-3. The black line indicates the boundary of the Hauraki Gulf Marine Park.

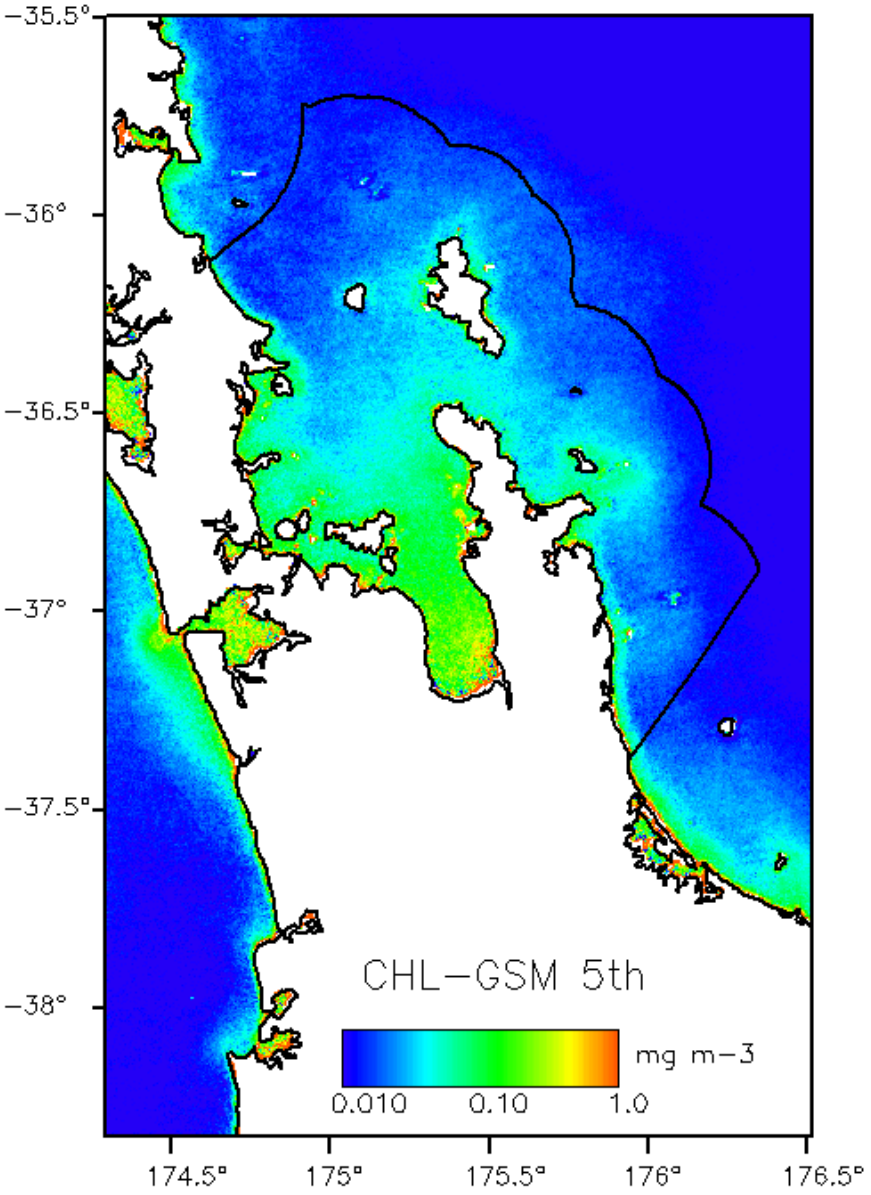

Figure 4-3: 5th percentiles of chlorophyll-a concentration (chl-a). Values obtained from the CHL-GSM algorithm (equation 2). Values are calculated as the 5th percentile at each pixel over 11 years of MODIS-Aqua data. Note different scale to Figure 4-1 and Figure 4-2. The black line indicates the boundary of the Hauraki Gulf Marine Park.

5 Discussion

Long term environmental observations have been carried out in the Hauraki Gulf region to understand the driving forces in the dynamics in phytoplankton biomass and its primary production. These have involved operational oceanographic samplings with water collections, moored instrumentation and satellite observations. This multi-sampling strategy was necessary to capture dynamics across spatial and temporal scales. Satellite observation of ocean colour is an effective complementary tool to *in situ* sampling, providing large-area (100s of km), long-term (years to decades) observations of coloured material in coastal zones over long periods. In this study, over a decade of in water collections, sampled at seasonal (3 month) intervals has been used here to assist with testing, selecting and tuning satellite processing algorithms for TSM and chl-a.

Some important limitations of the satellite-based approach must be recognised:

1. Ocean colour sensors only see material in the upper water column, typically from a few cm to a few metres of depth, depending on the turbidity of the water. In highly turbid waters, the satellite may only see material in upper few centimetres, whereas in offshore waters with lower turbidity, the satellite may see material in the upper tens of metres. Deeper suspended sediment and that near the sea-bed will usually not be seen in satellite data.

2. When the water is very shallow (less than a few metres) it is possible for the satellite to see the sea-bed through the overlying water. In this case, the estimate of suspended sediment concentration from the satellite data is likely to be too high, and the estimate of chl-a from the GSM algorithm is likely to be false. This situation is likely to be rare in the study region because shallow waters typically correspond with high suspended sediment loads so that the sea-bed is rarely visible to the satellite.

3. Ocean colour satellite data are not obtained when clouds are present, and this is the case for much of the time. In our data analysis, about 30% of the satellite observations were cloud free, which is fairly typical across New Zealand. Failure of the MODIS turbid water atmospheric scheme (Wang & Shi, 2007) also occurred in the study region in areas of higher sediment concentrations, leading to data loss nearshore. These two reasons for lack of valid data products are likely to introduce a bias into the data composites based on satellite data. Concentrations of TSM and possibly chl-a in the water column are likely to be positively related to the probability of cloud presence/absence. For example, concentrations of suspended sediment 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 TSM of chl-a based on satellite data are likely to underestimate the actual long-term concentrations.

4. As mentioned in (3), there was a high rate of failure of the NASA turbid-water atmospheric correction algorithm near the coast in the study region, and especially in the southern Firth of Thames. 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 TSM and chl-a in the study region.

5. Overall, satellite observations of TSM and chl-a are inherently less accurate than *in situ* measurements. In particular, estimates of chl-a in the presence of moderate concentrations of sediment are uncertain because the subtle effect of chl-a on ocean colour is masked by the stronger effect of sediment. Chl-a values in areas of high suspended sediment concentration are hence likely to have high uncertainty. Satellite observations and *in situ* observations (from vessels and moorings) are hence complementary and an integrated approach to monitoring will generally be most useful.

The main findings of this work are given below.

1. Comparison of satellite data with *in situ* measurements led to TSM in the study area being estimated via a scaling of the GSM semi-analytical algorithm estimate of particulate backscatter at 555 nm (TSM-GSM). This product explained 33% of the variance in the *in situ* TSM data set in log-log space (N=428). This is comparable with results in similar studies elsewhere.

2. Comparison of satellite data with *in situ* measurements led to chl-a in the study area being estimated via a scaling of the GSM algorithm estimate of phytoplankton absorption at 488 nm (CHL-GSM). This product explained 44% of the variance in the *in situ* chl-a data set in log-log space (N=138). This is comparable with results in similar studies elsewhere. Co-occuring suspended sediment had little effect on the CHL-GSM product.

3. Products were generated at a nominal-250 m spatial resolution and mapped onto a 500 m resolution grid for the region encompassing the Hauraki Gulf Marine Park. The long term median, 95th percentiles and 5th percentiles for TSM and chl-a were extracted from this 11-year dataset. These spatial summary datasets are provided electronically to Waikato Regional Council.

4. The long-term satellite composites show higher concentrations of TSM and chl-a inshore, and especially high concentrations in the Firth of Thames. The TSM values are comparable with data in other areas of New Zealand and for temperate coastal regions elsewhere in the world. The TSM values derived from the satellite data are low compared to near-bed measurements used for assessing effects of suspended sediment on filter-feeding bivalves. For example, Schwarz et al. (2006) found mussels to be adversely affected by suspended sediment at concentrations greater than about 100 g m^{-3} (which occurred rarely in the satellite dataset) and oysters to be affected at TSM greater than about 15 g m^{-3}.

5. The spatial distribution of chl-a is similar to that derived from *in situ* measurements alone, but long-term median concentrations in inshore regions are higher in the satellite data set (i.e. comparing Figure 1-1 and Figure 4-1) by about a factor of 2. This may partly be because field sampling can often miss episodic or short-duration productivity events that may be sampled by the satellite observation. Further investigation of this difference would be useful in the future.

6. Further developments in ocean colour algorithms are likely to improve the quality and reliability of data on TSM and chl-a in the study region. This research is ongoing internationally and is an active area of core-funded research at NIWA. As ocean colour processing methods improve and the time-series of satellite observations of the Hauraki Gulf region lengthens, at some stage it will be useful to update this analysis and regenerate the TSM and chl-a climatologies.

7. In the meantime, having developed this dataset, further summaries may be extracted relatively quickly as required.

6 Acknowledgements

Satellite data were provided by NASA Ocean Biology Processing Group and the MODIS-Aqua project team at Goddard Space Flight Center, Maryland, USA. MODIS-Aqua data since mid-2007 were received by the NIWA satellite X-band receiver in Lauder. The historical dataset is a compilation of many seasonal (3 monthly) research voyages to the region between 2002 and 2011, mainly on the *RV* Kaharoa. These *in situ* measurements in the region were supported by NIWA core funding, and we thank the funders, scientists, technicians and crew involved.

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Appendix A Number of pixels used in data complilations

The numbers of data points used in the annual compilations for TSM (Figure A-1) and chl-a (Figure A-2).

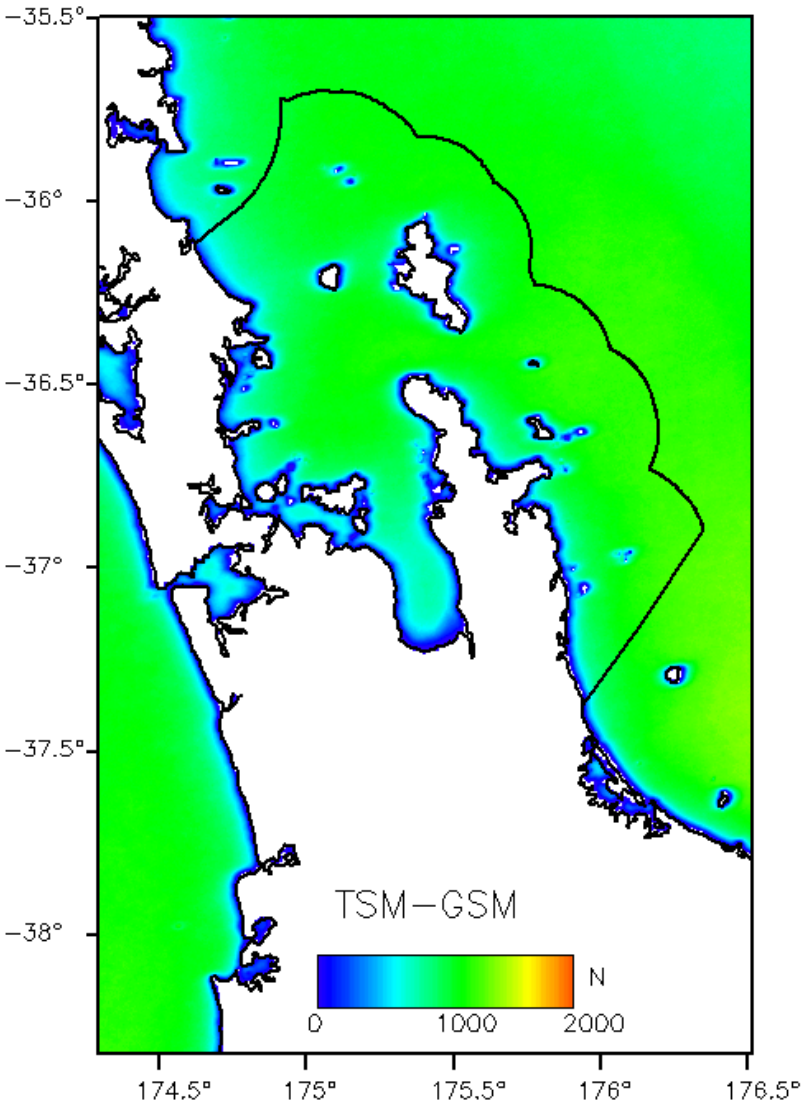

Figure A-1: Number of data points used in generating long-term TSM median. The relatively small number of valid points near the coast is mainly due to failure of the atmospheric correction processing over highly turbid waters. The black line indicates the boundary of the Hauraki Gulf Marine Park.

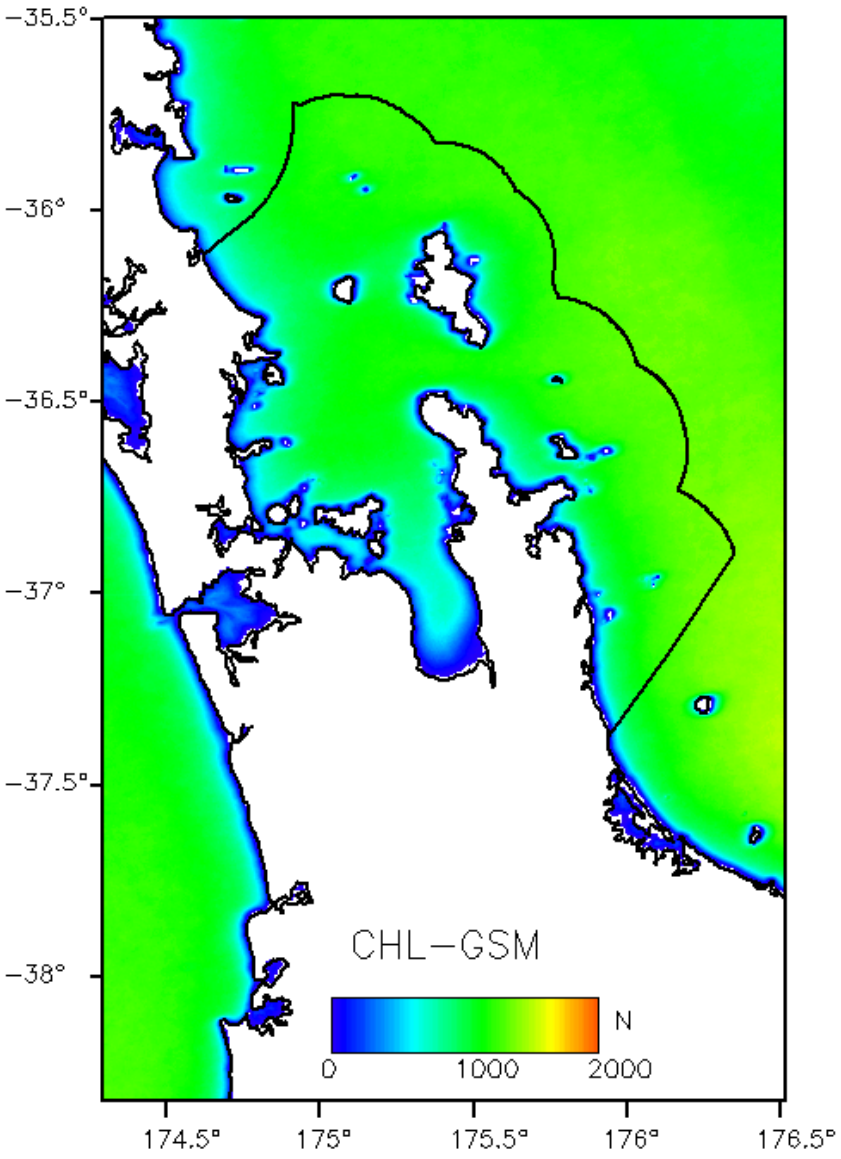

Figure A-2: Number of data points used in generating long-term chl-a median. The relatively small number of valid points near the coast is mainly due to failure of the atmospheric correction processing over highly turbid waters. The black line indicates the boundary of the Hauraki Gulf Marine Park.