CAWTHRON

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TREND ANALYSIS OF CHLOROPHYLL-*A* IN HAWKE’S BAY USING REMOTE-SENSING DATA: 2018–23

TREND ANALYSIS OF CHLOROPHYLL-*A* IN HAWKE'S BAY USING REMOTE-SENSING DATA: 2018–23

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Prepared for Hawke's Bay Regional Council

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EXECUTIVE SUMMARY

This report presents a revised trend assessment of surface chlorophyll-*a* (chl-*a*) concentrations as estimated from satellite measurements over the Hawke's Bay Coastal Marine Area (CMA) from 2018 to 2023. This is an update to a previous trend analysis that was conducted over a 15-year time series (2002–17) using a locally validated remote-sensing algorithm based on satellite data. Chlorophyll-*a* concentrations are used as a monitoring tool to estimate phytoplankton biomass. Phytoplankton play a pivotal role in primary production and nutrient cycling within marine ecosystems, and consequently, monitoring their biomass is commonly used for assessing marine environmental health.

Here we present the chl-*a* data from a locally validated Cawthron Institute (Cawthron) remote-sensing algorithm, data from the Hawke’s Bay Regional Council’s state of the environment (SOE) monitoring, and a NIWA-SCENZ (Seas, Coasts and Estuaries, New Zealand) chl-*a* product that offers New Zealand-wide coverage. This report presents four key analyses: an updated trend analysis, an analysis of seasonal patterns, a focus on chl-*a* trends in the region of the Awatoto coast, and a comparison of the Cawthron chl-*a* results with the NIWA-SCENZ product.

Trend analysis

A comparison between the recent 2018–23 trend analysis and the previous 15-year analysis revealed notable differences. While both analyses indicated increasing chl-*a* concentrations in summer, the newer analysis showed decreasing trends in autumn and winter, in contrast to previous increasing trends. These variations are primarily attributed to large-scale climatic patterns, particularly the El Niño and La Niña cycles and associated summer heatwave events that have occurred in recent years. Future analyses should consider these climate cycles and potential for future increased climate warming to understand consistent chl-*a* concentration differences during these events.

Seasonal patterns

The analysis reaffirms the strong seasonal patterns observed in chl-*a* concentrations, consistent with previous research. Chlorophyll-*a* concentrations were highest during winter and lowest during summer, with nearshore areas consistently exhibiting higher levels than offshore regions. The previous study assessed the potential influence of higher river flow-induced nutrient inputs on nearshore chl-*a* peaks, and our updated results align with the findings of this study.

Awatoto region

The Awatoto SOE site exhibited a high-confidence increase in surface chl-*a* concentrations over the past 5 years, with notable high measurements in late 2022 and early 2023. While the exact cause and ecological implications of this bloom remain uncertain due to limited data, further investigation is warranted. Additional SOE sites, including the HAWQi (Hawke’s Bay Water Quality Information) buoy, Mohaka, Wairoa and Westshore, also showed increasing trends and could be integrated into the analysis of Awatoto data.

Product comparison

Comparisons between monthly average NIWA-SCENZ chl-*a* and the Cawthron algorithm consistently indicated higher chl-*a* in SCENZ estimates in coastal waters. Given that Cawthron chl-*a* estimates tended to underestimate chl-*a* levels compared to physical water samples in the coastal environment, SCENZ chl-*a* estimates may be more accurate. However, direct comparisons of daily SOE data to monthly average NIWA-SCENZ data meant it was not possible to directly assess the accuracy the NIWA-SCENZ data. Monthly average SCENZ data also compared favourably to the locally validated Cawthron algorithm in offshore environments, with about 80% of the variance explained. While we have not conducted a validation of the NIWA-SCENZ data here, it appears this may be appropriate for assessing future chl-*a* trends in both the coastal and offshore areas of the region. Consequently, we would recommend that a separate study to validate the NIWA-SCENZ data for the region is undertaken.

Recommendations

To enhance marine environment management in the Hawke's Bay CMA, we propose a three-pronged approach:

1. *Fine-scale SOE monitoring*. Regularly analyse and compare the *in situ* (SOE water samples and moored fluorometry) data against historical values and seasonal norms. Results outside the normal range of variance should trigger in-depth investigations and responses, which could include analysis of wider-scale information provided by satellite data.
2. *Annual satellite chl*-a *comparisons*. Use surface chl-*a* data to identify broader chl-*a* patterns across the CMA. Conduct annual assessments, grouping data by seasons, and consider making these findings accessible to the public. Given that this study indicates that the nationally available NIWA-SCENZ data may perform better in nearshore environments, we would recommend undertaking a validation process to support its inclusion in future assessments.
3. *Trend analyses based on climate cycles*. Investigate chl-*a* trends in relation to El Niño and La Niña cycles and climate change–induced ocean warming. Analysing these patterns alongside the finer-scale data will provide valuable context for understanding long-term changes.

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1. INTRODUCTION

1.1. Background

Phytoplankton form the base of the food chain in marine environments and are responsible for primary production[1] and nutrient cycling. They are typically nutrient-limited in marine ecosystems and respond strongly to the availability of nutrients. Consequently, their abundance and community composition can be influenced by changes in natural nutrient availability (i.e. upwelling and mixing of the water column) driven by seasonal weather patterns, but also by excess nutrients in the water column from land-based or anthropogenic sources (Elvines et al. 2019). Due to these nutrient responses, phytoplankton biomasses are commonly used to assess the trophic status of marine ecosystems (Smith 2006).

In the marine environment, phytoplankton biomasses are commonly estimated by measuring chlorophyll-*a* (chl-*a*), the light-capturing pigment they contain. Chlorophyll-*a* levels are conventionally monitored through physical water samples or through *in situ* analysis of chl-*a* fluorescence. However, due to logistical constraints field sampling often fails to capture the full spatial and temporal variability of phytoplankton biomass. Phytoplankton sampling is regularly conducted by regional councils in Aotearoa New Zealand as part of their state of the environment (SOE) monitoring. In addition to these *in situ* measurements, chl-*a* concentrations can be estimated by differences in how light reflects from the surface of the ocean. Consequently, reflectance data collected by satellites provide high-frequency, long-term datasets that can supplement the conventional SOE monitoring approach.

The Cawthron Institute (Cawthron) has previously used satellite-based remote-sensing approaches to assess and provide trend analyses for water quality in the Hawke's Bay Coastal Marine Area (CMA). The initial work, conducted in 2014 (Jiang et al. 2014; Knight and Jiang 2014), developed a locally validated algorithm to assess chl-*a* concentrations in the water from variations in sea-surface reflectivity captured in satellite imagery around an offshore *in situ* buoy site (Jiang et al. 2017). The algorithm was developed using Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua data, which is captured daily, at a spatial resolution of approximately 1 km^2 and validated using fluorescence data from the Hawke's Bay Water Quality Information (HAWQi) buoy.

In addition to the Cawthron algorithm, other products exist that use and analyse the MODIS satellite data. NIWA-SCENZ (Seas, Coasts and Estuaries, New Zealand)[2] assesses a wide range of parameters from the available MODIS Aqua satellite data, including chl-*a* (Gall et al. 2022). The SCENZ chl-*a* product varies from the Cawthron

[1] Primary production refers to the fixing of inorganic carbon (e.g. carbon dioxide) to organic carbon, which provides energy to marine food webs.

[2] https://gis.niwa.co.nz/portal/apps/experiencebuilder/template/?id=9794f29cd417493894df99d422c30ec2

algorithm in that it takes a more sophisticated blended algorithm approach, where different algorithms are used in relatively clear coastal and oceanic waters (Case 1 water) and turbid (Case 2) conditions. The SCENZ product was developed to provide a New Zealand-wide dataset and has not been locally validated. As the SCENZ product was developed in collaboration with regional councils and funded by Envirolink, it is of interest to compare it to Cawthron algorithm products.

1.2. Scope

Hawke's Bay Regional Council (HBRC) would like to build on the previous trend analysis and algorithm development (Knight and Jiang 2018) to assess whether chl-*a* trends in the region have changed over the intervening period. To address this, we used the previous algorithm to assess chl-*a* trends over the last 5 years and compared them to the previous time series. In addition, HBRC expressed interest in understanding trends in the Awatoto region (Figure 1), and Envirolink requested a comparison between the Cawthron algorithm and the NIWA-SCENZ product. Therefore, three analyses are presented:

1. Updated trend analysis – replication of chl-*a* calculations from MODIS data and analysis for trends from the end of the previous time series to present, 2017–23.
2. Focused analysis of chl-*a* trends in the Awatoto region and comparison with measured chl-*a* (SOE monitoring data).
3. Comparison of the Cawthron algorithm results, NIWA-SCENZ product, *in situ* fluorescence data from HAWQi and physical (SOE) water samples. The purpose of this comparison is to allow HBRC to understand the different results from each method. It is not intended as a validation exercise.

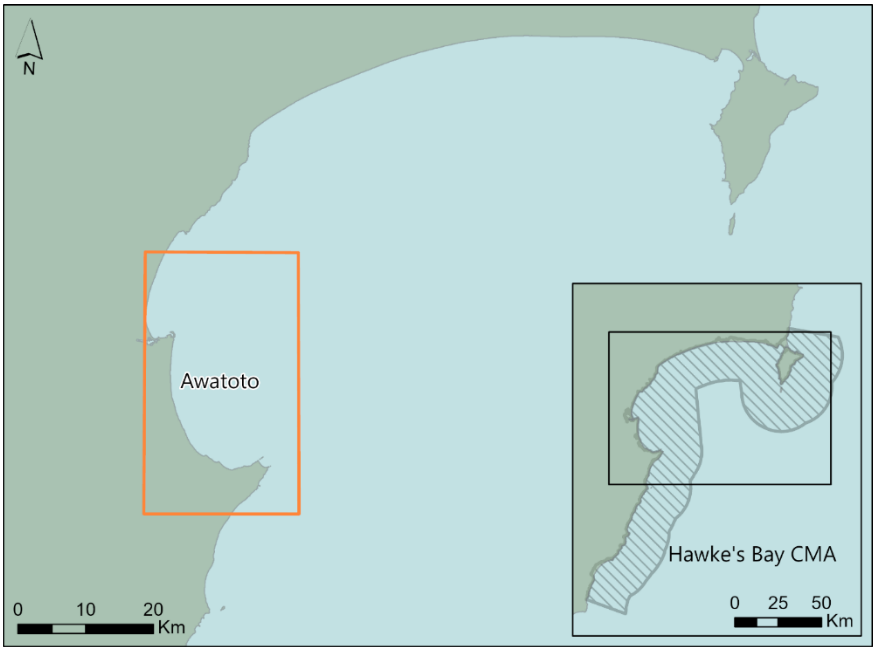

Figure 1. Awatoto region (orange box on main map) and Hawke’s Bay Coastal Marine Area (CMA; hatched area in inset).

2. METHODS

2.1. Data acquisition

2.1.1. Remote-sensing data

Remote-sensing data, acquired by the MODIS sensor on NASA's Aqua satellite and processed to generate a daily ocean colour radiance product, were sourced from NASA's EarthData[3] open data portal. Ocean_Ref_Daily_1KM (MYDOCGA)[4] is a Level-2G-lite product that is atmospherically corrected to account for radiance that is absorbed or scattered between reflecting off the ocean surface and exiting the atmosphere. The product comprises eight bands of remote-sensing reflectance (R_{rs}) between 405 nm (nanometres) and 877 nm.[5] Bands 9, 10 and 12 contain the reflectance ranges that correspond with peaks of absorbance for chl-*a* pigments (Figure 2), specifically:

- 438–448 nm = product layer: sur_refl_b09
- 483–493 nm = product layer: sur_refl_b10
- 546–556 nm = product layer: sur_refl_b12.

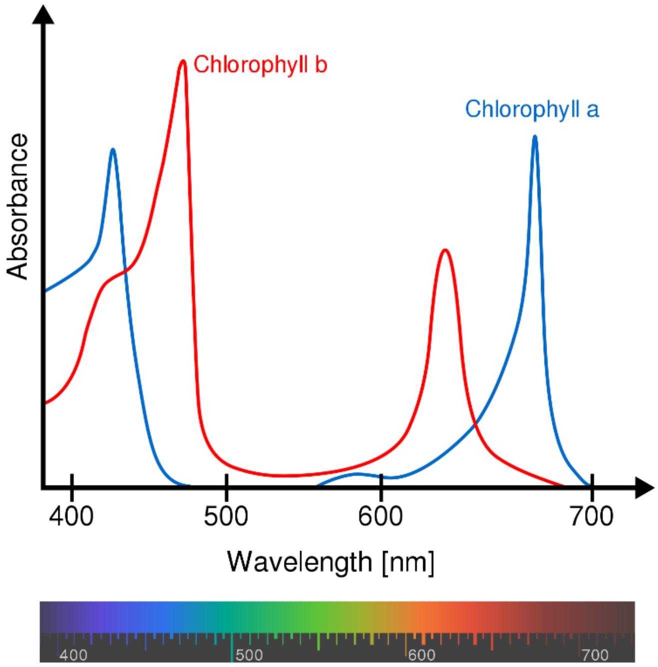

Figure 2. Absorbance spectra of free chlorophyll-*a* (blue) and chlorophyll-*b* (red) in a solvent. The action spectra of chlorophyll molecules are slightly modified *in vivo* depending on specific pigment–protein interactions. Source: 'Chlorophyll ab spectra' by Daniele Pugliesi, licensed under CC BY-SA 3.0.

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3 https://www.earthdata.nasa.gov
4 MODIS/Aqua Ocean Reflectance Daily L2G-Lite Global 1km SIN Grid – LAADS DAAC (nasa.gov)
5 MODIS Web (nasa.gov)

These daily product layers, along with corresponding data quality products (QA_b9, QA_b10, QA_b12), were acquired for the period 10 November 2017 to 26 February 2023 for the Hawke's Bay CMA. This was the limit of currently available data, as forward-processing of MYDOCGA Version 6 data was discontinued on 26 February 2023,[6] and Version 6.1 data products were not available at the time of data acquisition for this study. Data for the previously analysed time series were also downloaded to facilitate comparison across data that are based on the same processing version (6.0).

The R package MODIStsp (Busetto and Ranghetti 2016) was used to access and preprocess the data and to generate a time series of 1 km-resolution raster images for each band. The raster images were projected to a regular grid (New Zealand Transverse Mercator, ESPG:2193), using nearest-neighbour resampling method. The four-bit data quality products were used to generate masks to select only highest-quality data for each band (Vermote et al. 2015).

2.1.2. In situ *chlorophyll-*a *measurements*

Water quality is monitored at least every 2 months at a series of locations within the Hawke's Bay CMA as part of the SOE monitoring programme (Figure 3). Samples are collected from surface waters at all sites, except at the HAWQi monitoring buoy, where additional samples have been collected from a depth of 5 m since February 2020. Laboratory-analysed chl-*a* concentrations for SOE samples collected between 16 November 2017 and 16 March 2023 were supplied by HBRC for use in the time-series analysis.

Chlorophyll-*a* concentrations at 5 m depth are also measured hourly using a fluorescence sensor on the HAWQi moored monitoring buoy, located off the coast of Whirinaki (Figure 3). This fluorescent sensor (WETLabs Eco-FLNTU with an integrated anti-fouling Bio-wiper™) uses a 470/695 nm excitation-emission frequency to characterise the fluorescent signal with a stated chl-*a* sensitivity of 0.025 mg/m^3 (see Jiang et al. 2017 for more details). Data were acquired between 15 December 2019 to 22 March 2023, and summarised to provide daily mean chl-*a* for use in the time-series analysis. No data were available between November 2017 and December 2019, when the buoy was not operational.

2.1.3. *NIWA-SCENZ chlorophyll-*a *data product*

To facilitate comparison between remote-sensing chl-*a* calculated in this study and the NIWA-SCENZ chl-*a* product, data were extracted by NIWA staff for a series of sites within Hawke's Bay (Figure 3, blue). Sites were selected by Cawthron to align with a selection of SOE stations and to capture a gradient of inshore and offshore conditions.

[6] https://lpdaac.usgs.gov/products/mydocgav006

Due to the difference in resolution, chl-*a* data were acquired for nine 500 m resolution NIWA-SCENZ cells (a 3 × 3 cell box) surrounding each site.

The chl-*a* product generated by NIWA-SCENZ is based on Level 1A MODIS Aqua data, which are top-of-the-atmosphere reflectance measurements with higher spatial resolution (500 m) than Level 2 data. NASA's SeaDAS v7.2[7] software is used to calibrate, process and correct data for atmospheric scattering. Poor-quality data are masked, and chl-*a* is calculated using different methodologies for oceanic and coastal waters.

In Case 1 waters,[8] chl-*a* is estimated using the MODIS default (open-ocean) algorithm from NASA (R2018.0). In Case 2 waters,[9] where the open-ocean algorithm is less robust, chl-*a* is estimated by:

1. using the quasi-quantitative algorithm QAAv5 (Lee et al. 2002, 2009) to calculate phytoplankton absorption at 488 nm [aph(488)], and then
2. applying the chl-*a*-specific absorption coefficient, aph*(488). An average of New Zealand estuarine and lower-riverine measurements and oceanic phytoplankton values are used.

NIWA-SCENZ processing is documented in Gall et al. (2022). Data version 3.0, used in this report, includes an offshore extrapolation and interpolation to shorelines for monthly data gap-filling. Further details are also available on the NIWA-SCENZ website.[10]

[7] https://seadas.gsfc.nasa.gov

[8] Case 1 water refers to clear ocean waters, where phytoplankton concentrations are high compared to those of other particles (Morel and Prier 1977).

[9] Case 2 water refers to coastal waters, where phytoplankton pigment concentrations (i.e. chl-*a*) are low compared to those of inorganic particles (Morel and Prier 1977).

[10] https://gis.niwa.co.nz/portal/apps/experiencebuilder/template/?id=9794f29cd417493894df99d422c30ec2

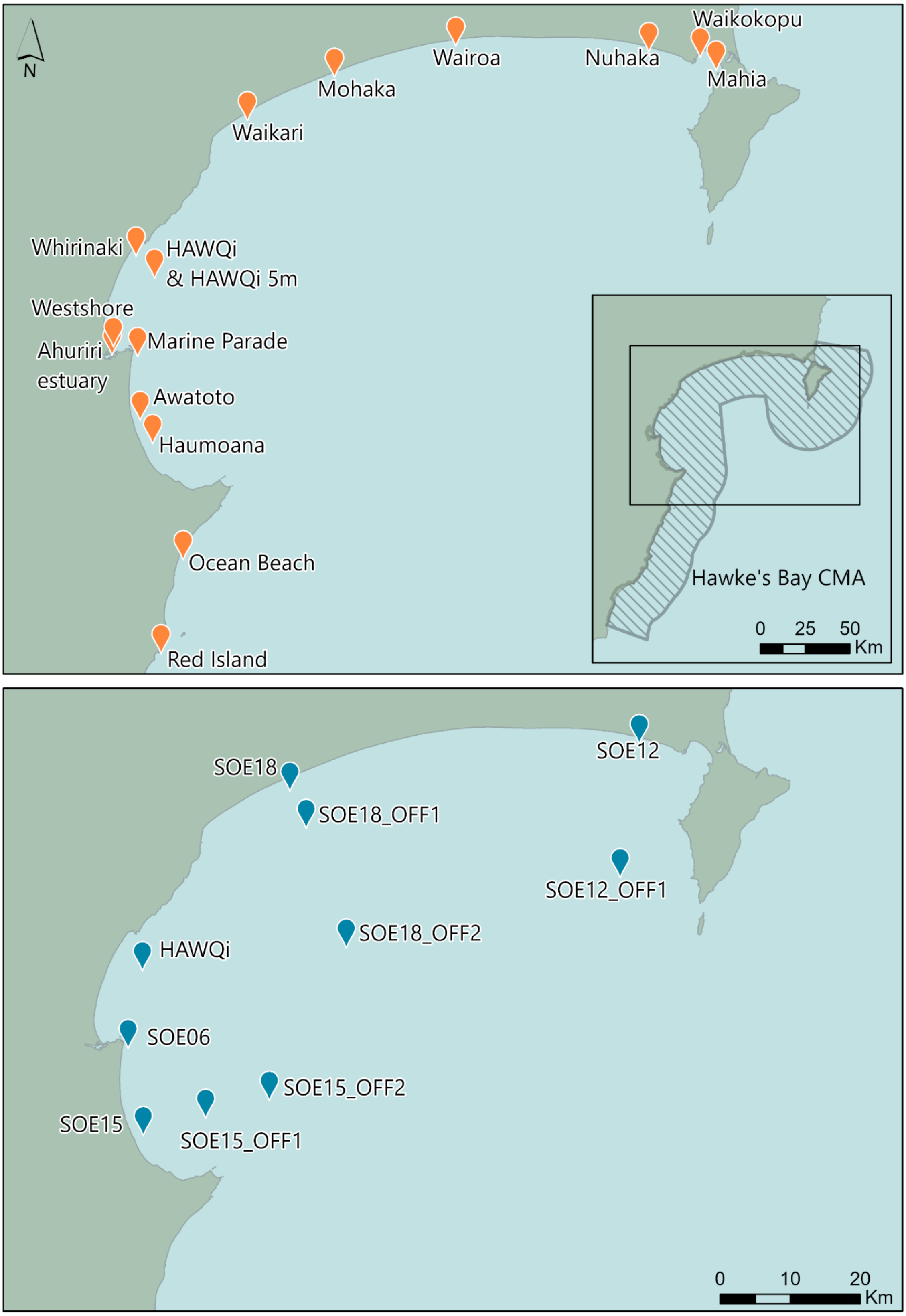

Figure 3. Locations of state of the environment water quality monitoring sites and the HAWQi buoy (orange markers) selected for comparison of this study's remote-sensing chlorophyll-*a* with NIWA-SCENZ chlorophyll-*a* product (blue markers) and the Hawke's Bay Coastal Marine Area (CMA, hatched area in inset).

2.2. Estimating chlorophyll-*a* using remote-sensing data

Chlorophyll-*a* concentration at the sea surface was estimated for the Hawke's Bay CMA using MODIS data and the locally validated, non-linear exponential model used for the previous analyses for this region (Jiang et al. 2017):

$$\text{Chl-}a = \text{a}.e^{-kS}$$

The model is based on R, a ratio of remote-sensing reflectance (R_{rs}) wavebands used in the OC3M algorithm to estimate global chl-*a* in oceanic waters (Knight and Jiang 2014). This provides a ratio of light at the blue (443 nm) peak of chl-*a* absorbance, to a minimum chl-*a* absorbance (555 nm).

$$R = \log_{10} (\max (R_{rs}443, R_{rs}448) / R_{rs}555)$$

The local exponential model removes the logarithm from R ($S = 10^R$) and incorporates model coefficients 'a' and 'k', which were fit to *in situ* chl-*a* monitoring data and the corresponding remote-sensing reflectance ratios (Knight and Jiang 2014). Coefficient values were defined as:

$$a = 14.791$$
$$k = 2.217$$

This Cawthron chl-*a* model was constructed from the HAWQi buoy located about 5 km from shore, in an area of relatively clear water (i.e. Case 1 water). The model was validated against an independent portion of the data (i.e. data not used to train the model) and shown to perform well (Jiang et al. 2014, 2017). Daily match-ups of satellite estimates were also subsequently compared to coastal SOE sites (i.e. Case 2 water) in Knight and Jiang (2014) and Jiang et al. (2014), and a reduction in performance was observed compared to the HAWQi data, with most sites showing poor agreement to data (Jiang et al. 2014). At three out of nine SOE sites considered by Jiang et al. (2014), a reasonable level of agreement (i.e. $R^2 > 0.5$) was observed; otherwise, the performance was poor (i.e. $R^2 < 0.5$). Consequently, when we describe the Cawthron chl-*a* estimates as 'locally validated', we refer to validation in Case 1 waters and urge caution in the interpretation of results from near-coastal waters (i.e. Case 2 waters) given that previous assessments showed variable performance at shallow-water sites (Jiang et al. 2014).

The Cawthron chl-*a* model was applied per pixel to the time-series RasterStacks of quality-masked MODIS reflectance data for bands 9, 10 and 12, using the 'Raster' R package (Hijmans 2023). To ensure that only sea-surface chl-*a* was included, data were masked using the Land Information New Zealand (LINZ) NZ Coastlines and Islands Polygons plus a 500 m buffer.

The resulting remote-sensing chl-*a* data layers were summarised to generate seasonal mean and standard deviation chl-*a* raster images for the current and previous time periods. Seasons were defined as:

- summer (December, January, February)
- autumn (March, April, May)
- winter (June, July, August)
- spring (September, October, November).

Results for each time series and season are presented in ArcGIS Pro (Version 3.0.1) using Stretch symbology (Minimum Maximum), matched to the dataset with the greatest range of values to facilitate comparison.

2.3. Time-series analysis

Analysis for trends was conducted at pixel-level across the CMA, using the remote-sensing chl-*a* raster images. Daily chl-*a* data between November 2017 and February 2023 were aggregated as mean chl-*a* for each combination of season and year. Since 10 November 2017 falls at the end of spring 2017, data from the rest of November were excluded and the time series began with summer 2018 (December 2017). Season-Year raster images were stacked per season (n = 6 for summer, n = 5 for all other seasons) and analysed for monotonic trends using Mann–Kendall trend analysis from the 'Kendall' R package (McLeod 2022). Masks for statistical significance were generated for each season by selecting values less than 0.05 from the 'sl' (two-sided p-value) output. The masks were applied to the Kendall score for each season, using the 'Raster' R package (Hijmans 2023). The results were presented using Unique Values symbology in ArcGIS Pro (Version 3.0.1).

Daily remote-sensing chl-*a* data were extracted at SOE monitoring sites and the HAWQi buoy and aligned with observed chl-*a* data reported at these locations. This dataset was deseasonalised[11] and then the time series was analysed using Sen's slope method. This non-parametric method is widely used to measure trends in time-series data and is calculated by taking the median of all possible slopes between the data points. Sen's slope is a robust approach to trend analysis for time-series data as the use of the median makes it less sensitive to outliers (Helsel and Hirsch 2002). To conduct the analyses, we used the process, functions and scripts developed by Land Water People (Snelder and Fraser 2019) in the R environment. The output of this analysis is a measure of confidence that is used instead of a p-value, as employing traditional two-sided hypothesis testing can be inappropriate for Sen's slope analysis (Broekhuizen and Plew 2018). Confidence levels for the trend direction are used as an alternative and can be categorised into likelihood categories (Table 1).

[11] Raw data was deseasonalised by subtracting the appropriate monthly median value from each of the raw values.

Table 1. Likelihood categories from McBride (2019).

Term	Likelihood of outcome
Virtually certain	99–100%
Extremely likely	95–99%
Very likely	90–95%
Likely	66–90%
About as likely as not	33–66%
Unlikely	10–33%
Very unlikely	5–10%
Extremely unlikely	1–5%
Exceptionally unlikely	0–1%

2.4. Comparison with NIWA-SCENZ chlorophyll-*a* product

Daily remote-sensing chl-*a* data constructed using the Cawthron model were extracted at 'NIWA-SCENZ comparison sites' (Figure 3, blue markers) and summarised to match the format of NIWA-SCENZ chl-*a* data, which were supplied as monthly median values.

At each site, four of the nine NIWA-SCENZ (500 m) raster image cells that coincided with the Cawthron chl-*a* (1 km) raster image cell were selected. NIWA-SCENZ chl-*a* data from these four cells were summarised as means and medians, in preparation for comparison.

Linear regression models were fitted to analyse the relationship between the two chl-*a* products. R-squared values and slopes were extracted from these models to assess how the products differed from one another.

3. RESULTS

3.1. Remote-sensing chlorophyll-*a*

A strong seasonal pattern was evident in remote-sensing chl-*a* data between December 2017 and early February 2023 (we did not include data during or after Cyclone Gabrielle; Figure 4). Visual inspection of the data indicates that mean chl-*a* was highest in winter and autumn, with elevated levels extending offshore in the Awatoto region and in northern Hawke's Bay. Chlorophyll-*a* was typically higher in nearshore waters than offshore waters during all seasons. The pattern of these results is consistent with the previous study, which also found that the highest chl-*a* concentrations were in the winter during the 15-year time series (Knight and Jiang 2018, replicated in Figure 4).

Seasonal patterns in the variability of chl-*a* were also apparent in the time series (Figure 5), with higher levels of variability in summer and spring compared to winter and autumn. During summer and spring, chl-*a* variability was typically highest in coastal waters, particularly around the Awatoto region.

Spatial trends in the remote-sensing chl-*a* data differed between the seasons (Figure 6). In summer, increasing trends of chl-*a* were observed within Hawke's Bay, particularly around the Māhia Peninsula. Whereas, for autumn and winter, chl-*a* trends were typically decreasing within the CMA. In spring, no pattern of significant trends was observed within the CMA, and sporadic areas outside of the CMA had mildly increasing trends.

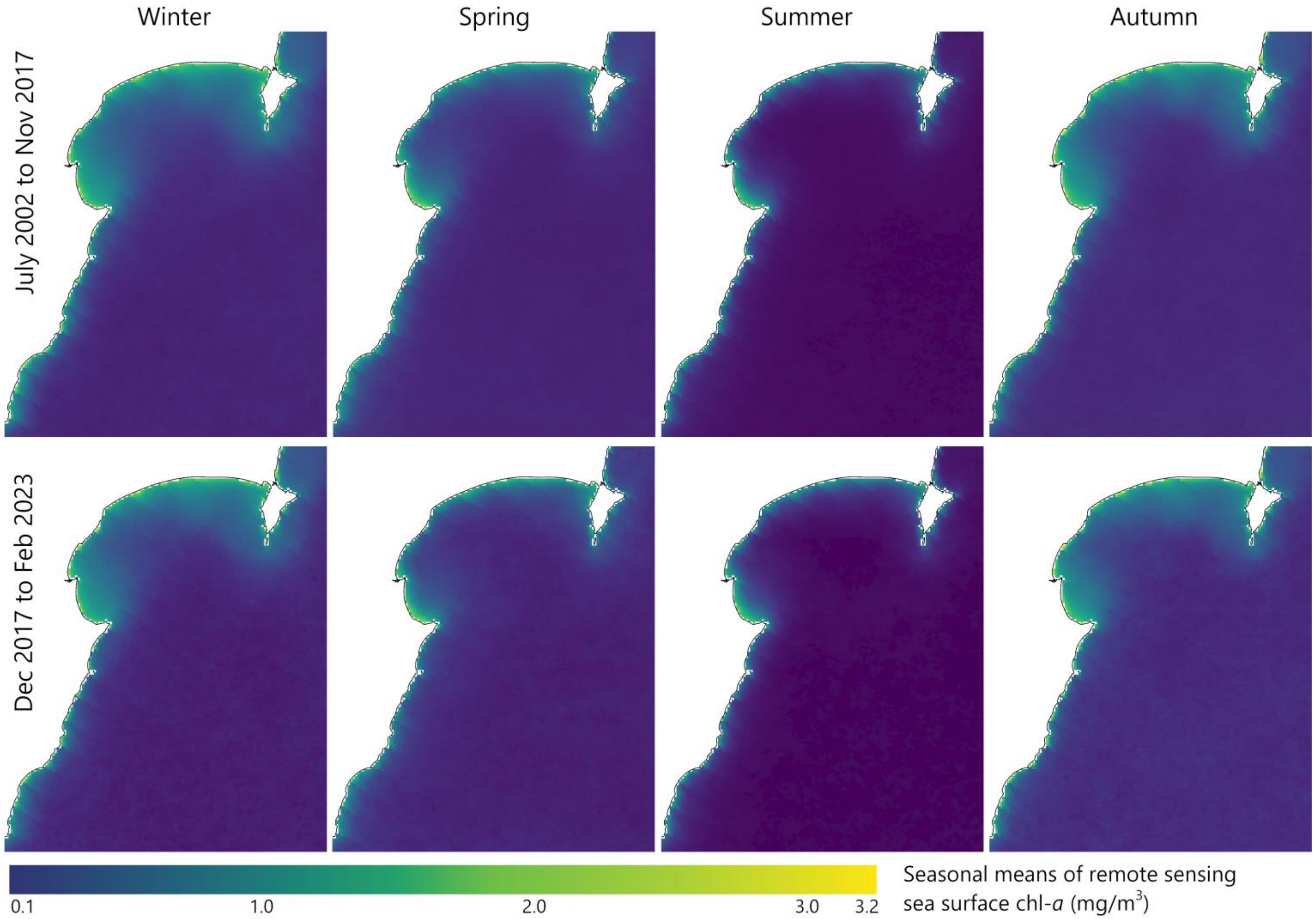

Figure 4. Mean seasonal chlorophyll-*a*, calculated from MODIS remote-sensing data using a locally validated exponential model, across previous and current time periods.

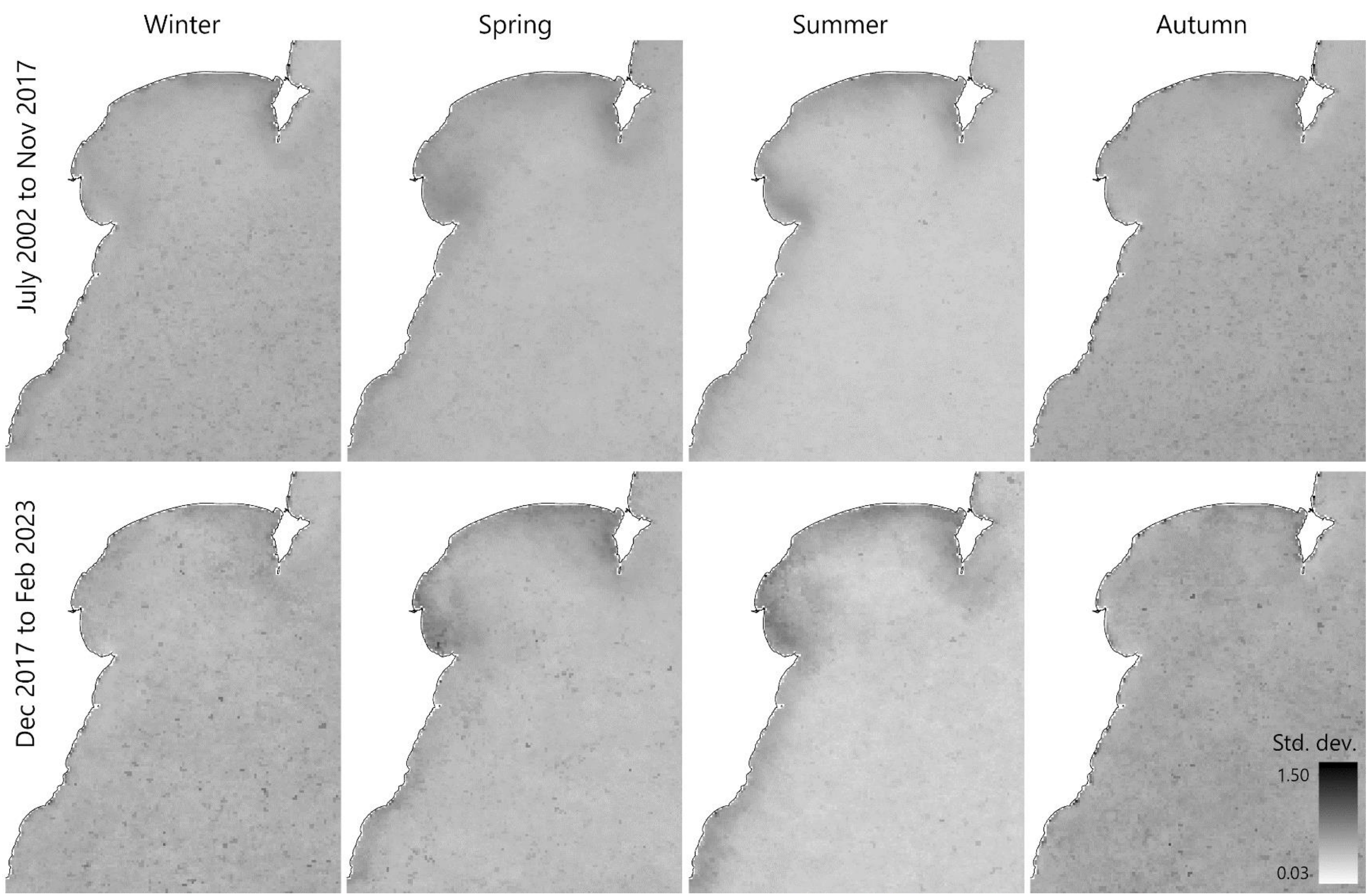

Figure 5. Standard deviation of seasonal remote-sensing chlorophyll-*a*, across previous and current time periods.

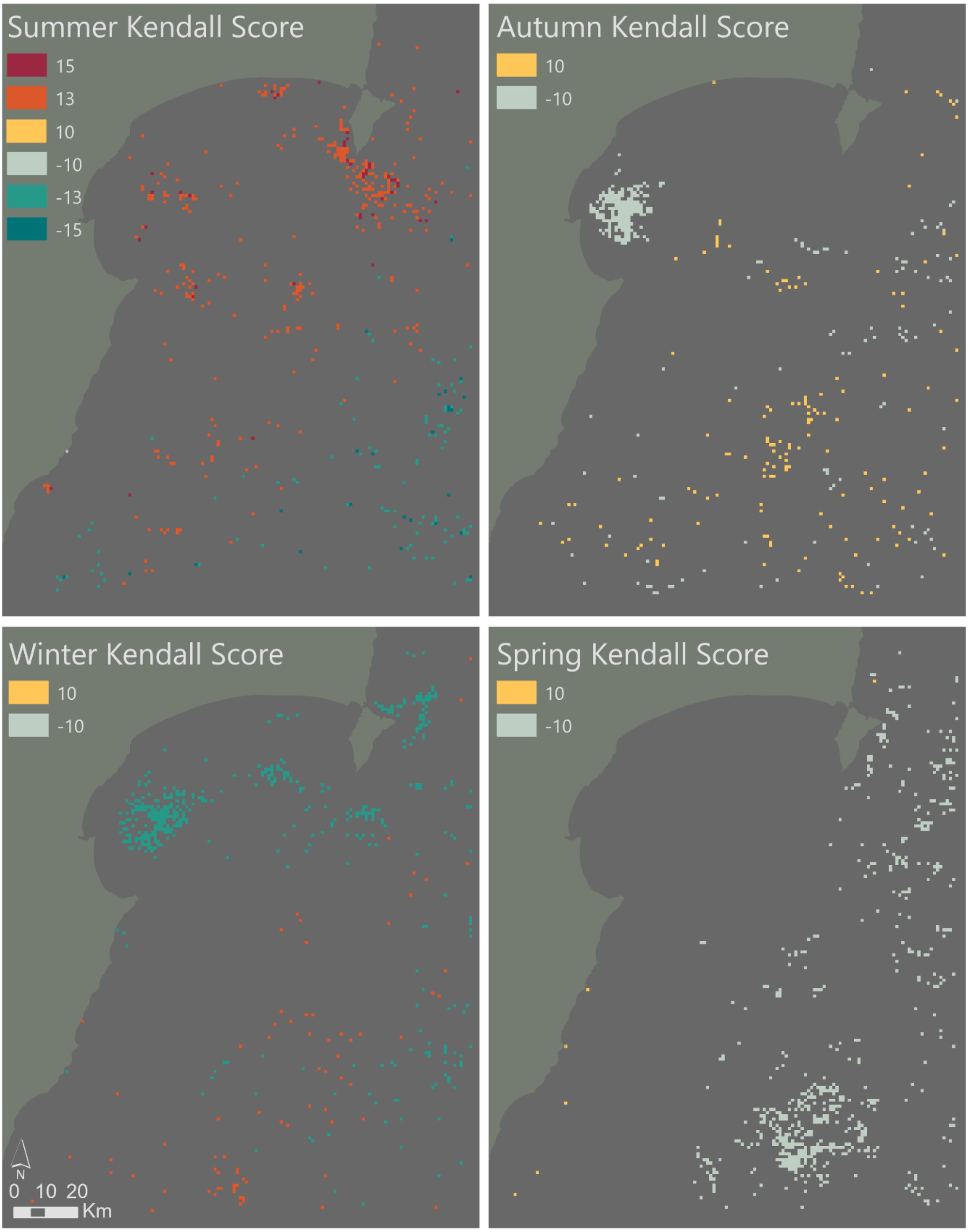

Figure 6. Statistically significant dimensionless Mann–Kendall scores for each season during the current time period (December 2017 to February 2023) in the Hawke's Bay Coastal Marine Area. Negative and positive scores indicate decreasing and increasing long-term trends, respectively, in chlorophyll-*a* for each season.

3.2. Awatoto region

Nearshore trends in remotely sensed chl-*a* concentrations were similar between the seasons for both the previous 15-year and recent 5-year trend analyses in the Awatoto region (Figure 7). Further from shore, the concentrations were similar to those in the rest of the CMA, where the highest levels of chl-*a* were observed in winter and autumn. Spatial within-season trend analysis of these data did not suggest any significant trends in chl-*a* across the Awatoto region.

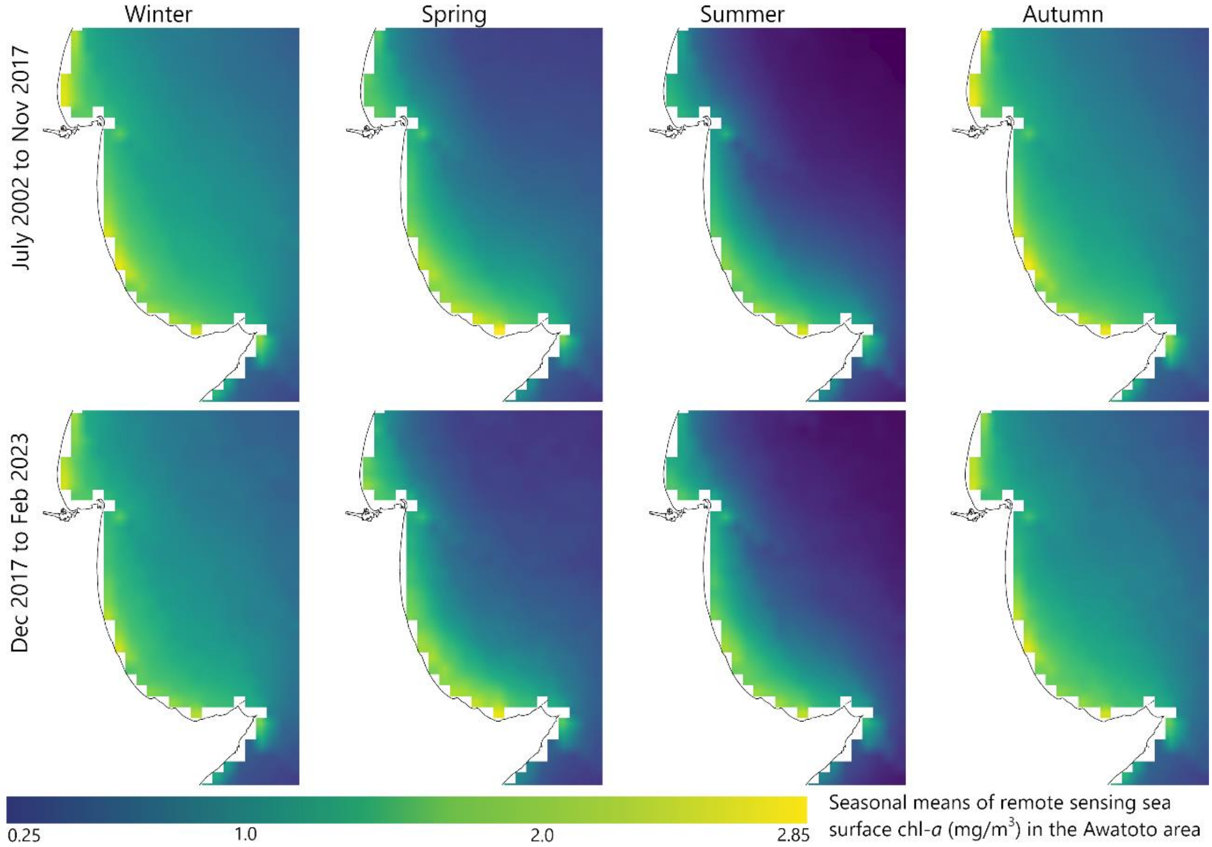

Figure 7. Mean seasonal chlorophyll-*a*, calculated from MODIS remote-sensing data using a locally validated exponential model, in the Awatoto region across the previous 15-year time period and the current 5-year time period.

In addition to the trend analyses conducted over the entire CMA and the Awatoto region, trend analyses using Sen's slopes were conducted on the data from *in situ* physical water samples from the SOE monitoring programme (Figure 8) and the remote-sensing data extracted at the Awatoto SOE station (Figure 9). The analysis of the SOE monitoring data at Awatoto showed an increasing trend of chl-*a* at the site, with high confidence (0.99%), whereas the remote-sensing data did not show a high-confidence increasing trend. The SOE monitoring observed a number of high values (i.e. > 5 mg/m^3) at the station throughout the monitoring period; however, these were consistently high throughout 2022, likely leading to the observed increasing trend. A similar pattern of higher-than-typical observations in late 2022 was also apparent in the remote-sensing dataset. However, the increases in the remotely sensed chl-*a* values were not consistent enough in 2022 for a trend to be recognised as significant. Sen's slope analyses were also conducted for the other SOE stations in the CMA, and high-confidence increasing trends were observed at the HAWQi buoy, Mohaka, Wairoa and Westshore (Table 2).

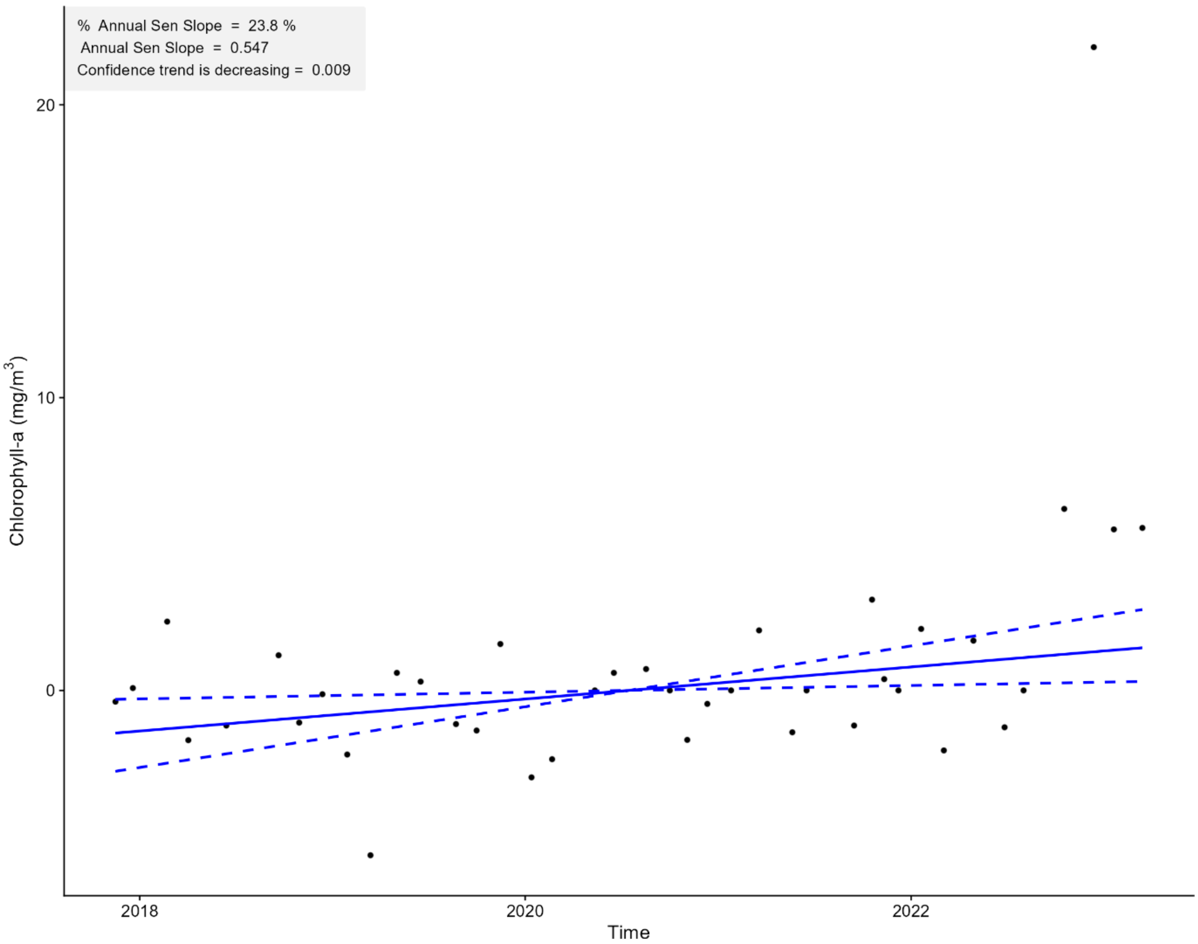

Figure 8 Trend analysis of the chlorophyll-*a* concentrations from the physical water samples collected at the Awatoto state of the environment station over a 5-year period. The analysis was conducted using Sen's slopes on deseasonalised data. Solid blue line indicates = best-fit Sen's slope line fitted through the deseasonalised data; dashed blue lines = 90% confidence intervals for the slope.

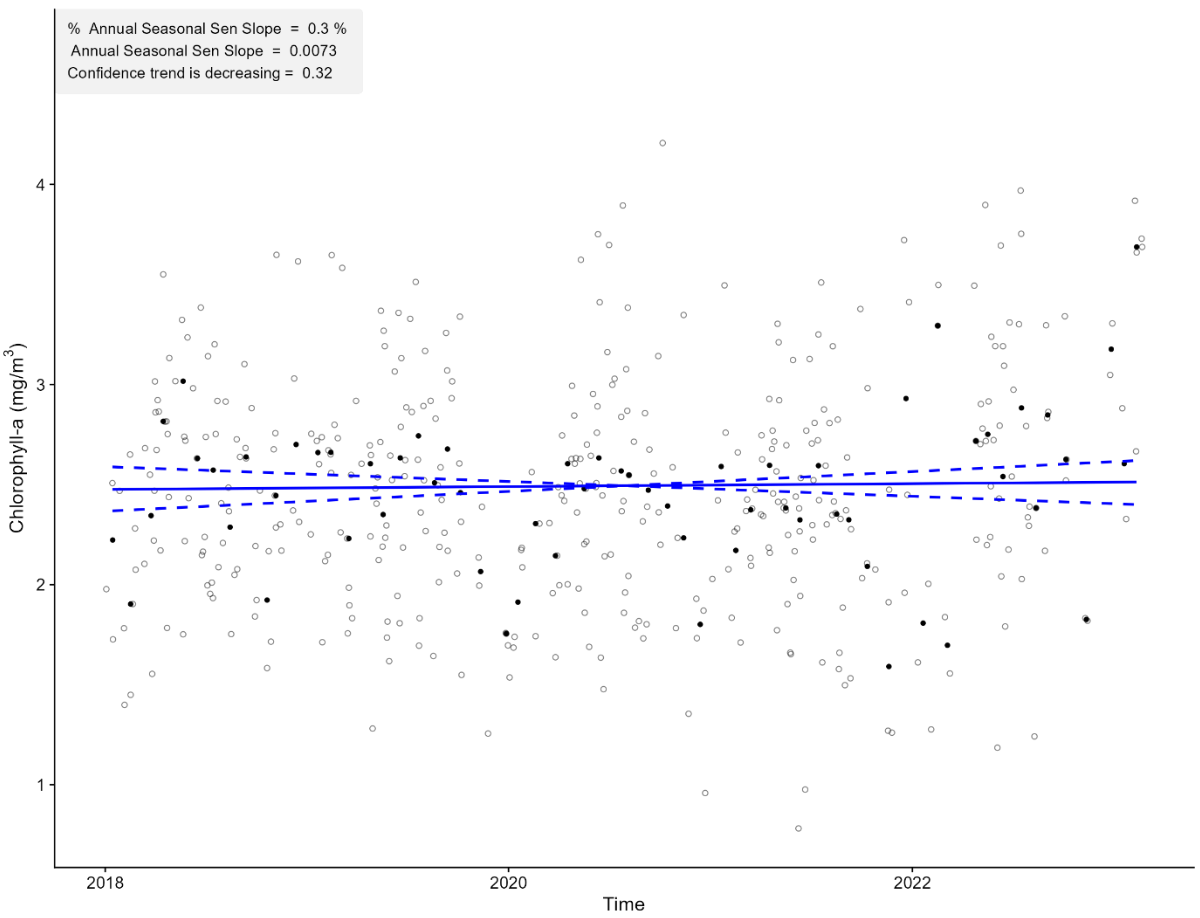

Figure 9 Trend analysis of the chlorophyll-*a* concentrations from the remote-sensing data from the Awatoto state of the environment station over a 5 year period. The analysis was conducted using Sen's slopes on deseasonalised data. White circles = raw data; black circles = observations (season median); solid blue line = best-fit Sen's slope line fitted through the deseasonalised data; dashed blue lines = 90% confidence intervals for the slope.

Table 2. Sen's slope analysis of the chlorophyll-*a* concentrations recorded from physical water samples at the state of the environment stations from 2018 to 2023 in the Hawke's Bay Coastal Marine Area. Bold sites indicate high-confidence trends and are those above 90% or 'very likely' as defined by McBride (2019).

Site	Percent annual change	Annual Sen's slope	Confidence
Awatoto	**26.20**	**0.60**	**0.99**
Haumoana	0.27	0.01	0.50
HAWQi 5m	-2.16	-0.02	0.50
HAWQi	**16.42**	**0.15**	**0.99**
Māhia	11.92	0.09	0.78
Marine Parade	10.35	0.15	0.83
Mohaka	**12.72**	**0.15**	**0.96**
Nuhaka	-1.22	-0.01	0.57
Ocean Beach	-0.51	0.00	0.51
Red Island	1.50	0.01	0.51
Waikari Coastal	13.65	0.09	0.81
Waikokopu	3.10	0.02	0.55
Wairoa	**10.27**	**0.11**	**0.95**
Westshore	**17.43**	**0.21**	**0.97**
Whirinaki	2.51	0.02	0.58

3.3. Product comparison

Overall, the Cawthron algorithm and NIWA-SCENZ produced quite different results (Figure 10), with SCENZ typically assessing the chl-*a* concentrations to be higher than the Cawthron algorithm. In addition to this observation, there is a clear pattern in how the two approaches preformed at the different sites (Table 3). At the offshore sites, the SCENZ and the Cawthron algorithm showed a strong relationship (Pearson's R^2 of means = 0.76–0.88; medians = 0.75–0.88), and at the inshore sites on the SOE stations the primary differences were seen (Pearson's R^2 of means = 0.26–0.32; medians = 0.08–0.36). The only outlier to this was SOE18, which had the strongest relationship between the two products for an inshore site (Pearson's R^2 of means = 0.75; medians = 0.75). Among all the sites, the slopes of the relationships ranged from 0.96 to 2.83, showing that the SCENZ product estimate of the chl-*a* concentrations was higher than the Cawthron algorithm in both nearshore and offshore waters.

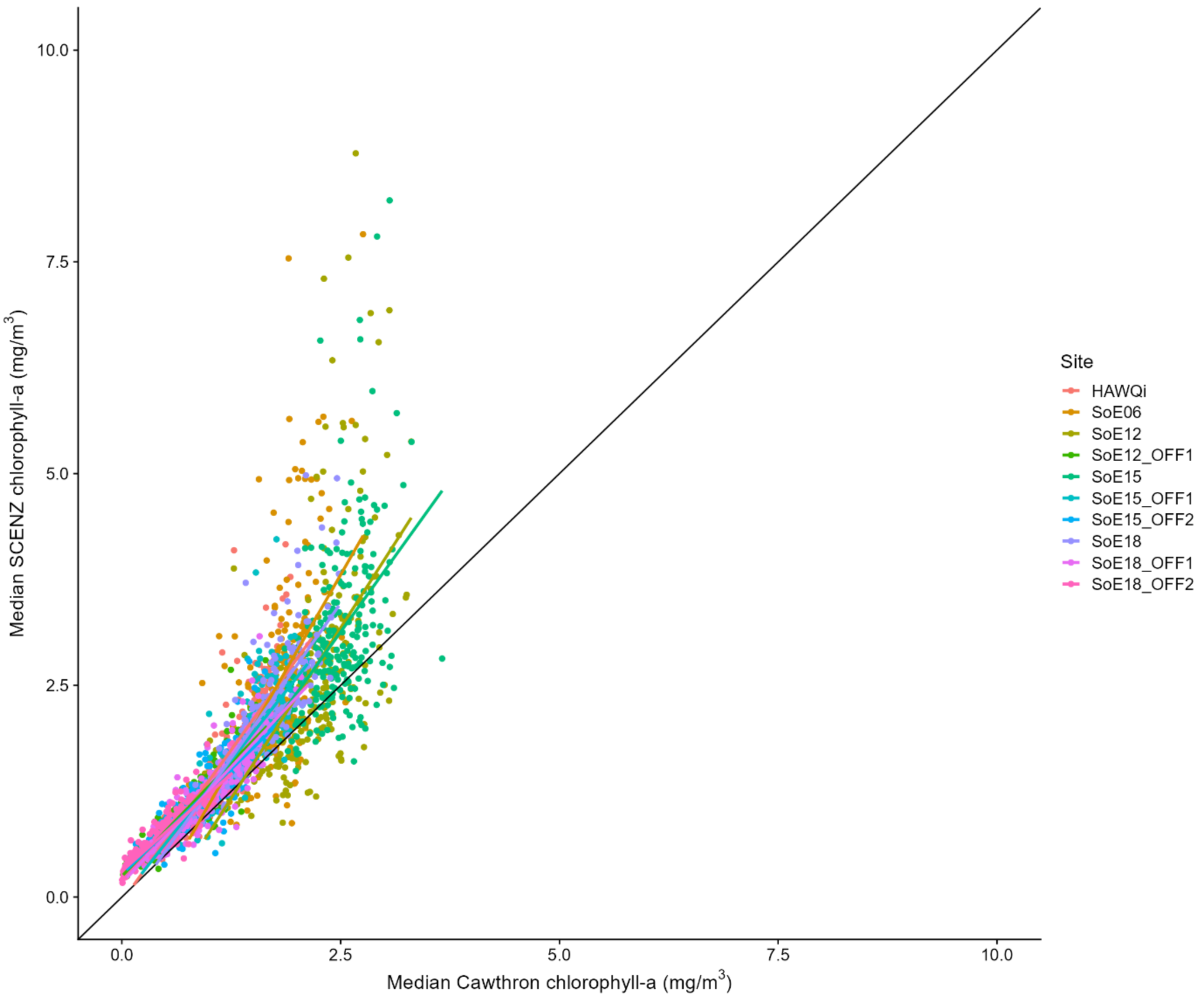

Figure 10. Comparison of the monthly median chlorophyll-*a* concentrations assessed by the NIWA-SCENZ and Cawthron models at selected coastal and offshore locations. Data presented are the monthly means for each of the different sites (indicated by different colours) between 2018 and 2023. The black line is the one-to-one line indicating a perfect relationship. Note that two SCENZ values greater than 10 have been excluded by the choice of axes limits.

Table 3. Comparison of the performance of the Cawthron algorithm and NIWA-SCENZ product assessing the monthly chlorophyll-*a* concentrations at sites throughout the Hawke's Bay Coastal Marine Area. This was conducted using the R-squared values and slopes for the linear models analysing the means and medians of the aggregated data.

		Mean		Median	
SITE	**Site location**	**R-squared**	**Slope**	**R-squared**	**Slope**
HAWQi	HAWQi	0.76	1.62	0.78	1.43
SOE06	Inshore	0.26	2.05	0.23	1.93
SOE12	Inshore	0.32	1.72	0.36	1.61
SOE12_OFF1	Offshore	0.88	1.20	0.88	1.07
SOE15	Inshore	0.21	2.83	0.08	1.68
SOE15_OFF1	Offshore	0.78	1.48	0.76	1.31
SOE15_OFF2	Offshore	0.82	1.15	0.79	1.00
SOE18	Inshore	0.75	1.51	0.75	1.46
SOE18_OFF1	Offshore	0.82	1.18	0.84	1.10
SOE18_OFF2	Offshore	0.75	0.96	0.84	0.92

4. DISCUSSION

Overall, this updated analysis of chl-*a* concentrations in the Hawke's Bay CMA found strong seasonal patterns that were similar to the previous analysis (Knight and Jiang 2018). However, there were variations in spatial trends between the two long-term trend analyses, and interesting results from the SOE monitoring data and comparison with the SCENZ chl-*a* product. These variations and results provide insight into how the HBRC can use these different approaches and tools to manage the marine environment in Hawke's Bay CMA.

4.1. Trend analysis

As with the initial Cawthron remote-sensing trend analysis, this analysis found that chl-*a* concentrations were highly seasonal. Winter typically had the highest concentrations of chl-*a* and summer the lowest. In all seasons, nearshore areas of the CMA had higher concentrations of chl-*a* than offshore areas. The previous trend analysis associated some of these nearshore peaks with nutrient input from river flows, a relationship that has also previously been identified in the Marlborough Sounds (Zeldis et al. 2008). However, it is also worth noting that estimates of chl-*a* derived from remote sensing can be affected by elevated turbidity driven by the same riverine inputs.

The results from the 2018–23 trend analysis observed different trends in chl-*a* concentrations to the previous 15-year trend analysis (Knight and Jiang 2018). These differences were apparent in all seasons. Summer was the only season where both analyses suggested that chl-*a* concentrations were increasing, particularly around Māhia Peninsula. Significant trends were detected in only a small proportion of the CMA and wider Hawke's Bay Region. However, the more recent analysis suggested that chl-*a* concentrations were decreasing for autumn and winter, in contrast to the increasing trends previously observed. In addition, the current analysis observed sporadic decreases in the offshore CMA in spring compared to the large-scale decrease observed throughout the northern CMA in the 15-year time series. It is important to note that trends across different time spans might not be directly comparable and should be considered in the context of inter-annual and multi-year natural climate variability.

As significant trends are largely observed offshore and vary throughout the seasons, the primary driver is likely large-scale climatic patterns. The climate influences phytoplankton concentrations as changes to wind and current can affect upwelling patterns and subsequent nutrient availability, which is particularly important in the summer months. Similarly, cloud cover can affect light availability in winter months, when sunlight can also be limiting. The primary drivers of these conditions in coastal Aotearoa New Zealand are El Niño and La Niña weather patterns, which are quantified by the Southern Oscillation Index (SOI). The SOI shows that the majority of the recent analysis (2018–23) was in a La Niña phase (SOI > 0), whereas between 2002 and 2017 the El Niño–Southern Oscillation (ENSO) switched between El Niño and La Niña cycles several times.[12] A new El Niño phase began in June 2023. Future analyses in Hawke's Bay CMA could take these large-scale events into account to observe whether they result in consistent differences in chl-*a* concentrations.

In addition to climate cycles, there are also consistent global warming trends that are present in warming marine waters around Aotearoa New Zealand (Sutton and Bowen 2019). Given the potential cumulative impacts of such warming on coastal waters, understanding how these changes are affecting the coastal environments of the Hawke's Bay CMA can also be gathered through inclusion of the broad-scale information provided by remotely sensed satellite data.

4.2. Awatoto region

State of the environment monitoring data suggests that chl-*a* at the Awatoto SOE site has increased with high confidence over the past 5 years. This pattern has been primarily driven by a steep increase in the chl-*a* concentrations throughout late 2022 and early 2023. Without detailed phytoplankton community data or other ecological information, it is difficult to assess the cause or likely effects of this increase, but it should be investigated further if these high readings continue. Trend analysis of the wider SOE data also indicated increasing chl-*a* concentrations at the HAWQi buoy, Mohaka, Wairoa and Westshore, which should be included in any analysis of the Awatoto data.

While the remote-sensing chl-*a* data did not provide the same confidence in the increasing trend, a similar spatial pattern in concentrations to that presented in Knight and Jiang (2018) was observed. The initial development of the algorithm noted that the remote-sensing data typically underestimates chl-*a* concentrations and is not a good indicator for some of the inshore sites. In addition to this, remote-sensing data were often not available or not of sufficient quality for the dates when extremely high chl-*a* concentrations were detected at other SOE samples – for example, at Westshore (47 mg/m^3 on 13 December 2022 and 66 mg/m^3 on 20 January 2023) and Marine Parade (62 mg/m^3 on 20 January 2023) when an 'algal bloom' event occurred.

4.3. Product comparison

When comparing the monthly medians and means, the NIWA-SCENZ product consistently estimated higher levels of chl-*a* than the Cawthron algorithm. As has

[12] See, for example, SOI data here: https://www.ncei.noaa.gov/access/monitoring/enso/soi

been shown in the previous report, the Cawthron model is typically an under-representation compared to the physical water samples. Some of this difference may be due to the sample sizes considered, where SOE sample sizes may be up to a litre of water at a single sampling site, while the volumes associated with remote sensing 1 km^2 of ocean are many thousands of cubic metres of water; consequently, values are likely to be very different.

While we have not validated the SCENZ product in this report, it is possible that it provides a more accurate representation than the Cawthron algorithm given the higher concentrations observed. In the offshore environment, SCENZ was typically within 80% of the variance of the locally validated Cawthron algorithm, suggesting that both datasets produce similar results in these environments. In the coastal environment, where the Cawthron model has been shown to have poor performance in the past and where the SCENZ product takes a more sophisticated approach to the Case 2 waters, the results from SCENZ may be more accurate.

4.4. Recommendations

We recommend that HBRC adopts a three-pronged approach for using *in situ* measurements (water sampling and moored fluorometry) alongside satellite-derived chl-*a* data to gain insights into changes in the marine environment:

1. For fine-scale SOE monitoring based on *in situ* water sampling, laboratory analysis and fluorometric data from the mooring, we advise that current monitoring results are regularly compared with data from previous years and seasons. If the results fall outside the normal range of variance, it should trigger a more comprehensive and in-depth response to investigate the underlying causes. This could include wider-scale analysis that uses satellite, remotely sensed, chl-*a* and other data.

2. We recommend that wider patterns in the Hawke's Bay CMA continue to be investigated, using satellite-derived surface chl-*a* data to identify broader patterns across the CMA. This analysis can be conducted on an annual basis by grouping months into seasons and carefully examining trends and updates. Given some evidence in this study that the nationally available NIWA-SCENZ data may perform better in nearshore environments, we would recommend undertaking a validation process to support its inclusion in future assessments.

3. For a broader context and understanding, we recommend conducting trend analyses based on ENSO cycles and climate change–induced warming trends at the wider Hawke's Bay scale. By observing how these cycles are changing and their potential impact on chl-*a* trends, we will be able to discern variations in patterns over time. The Cawthron chl-*a* model, which can provide access to

daily data and is shown to be reliable in offshore waters consistent with the NIWA-SCENZ product, appears to be suitable for this type of Case 1 (oceanic water) analysis. Daily data underlying the SCENZ weekly, monthly, seasonal and annual products are also available and should be investigated alongside other daily satellite and *in situ* information.

Alongside these regional recommendations, Envirolink is positioned to coordinate a national-scale approach to the assessment of marine water quality. The following recommendations are presented in this context and provide an overview of what is required for an effective national-scale strategy. This strategy would aim to ensure consistency in the collection and analysis of surface waters, verify the NIWA-SCENZ chl-*a* data in nearshore environments and support national-scale water quality trend analyses:

Consistency in surface water collection

- Continue in-water SOE surface collections at critical sites to support long-term inventories, and increase the number of observations to improve the power of statistical discrimination.
- Consider increasing the frequency of collections to monthly (minimum) at reviewed locations of interest to improve seasonal representativeness.
- Assess the power of this monitoring to detect trends by characterising the magnitude of variability versus change.

Verify NIWA-SCENZ chlorophyl-*a* data in nearshore environments

- Validate the accuracy and reliability of NIWA-SCENZ chlorophyll-*a* data specifically in nearshore ‘turbid’ environments.
- Assess the suitability of satellite chlorophyll-*a* data for inclusion in SOE reporting for the broader region, comparing the advantages, disadvantages and statistical power of remote sensing relative to (or in conjunction with) *in situ* monitoring to detect trends, monitor for change and support management actions.

Support national-scale water quality trends initiatives

- Review methods for analysing coastal water quality trends from different observational efforts (platforms) in consideration of climate scales of variability. This should encompass multi-year shifts, longer-term multi-decadal trends and non-linear analytical approaches.
- Undertake statistical power analysis on in-water collections, moored instrumentation and satellite datasets. This analysis will provide essential context regarding variability and establish a minimum sample size necessary to confidently determine changes over the desired scales of interest.

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6. REFERENCES

Broekhuizen N, Plew D. 2018. Marlborough Sounds water quality monitoring: review of Marlborough District Council monitoring data 2011–2018. Hamilton: National Institute of Water and Atmospheric Research. NIWA Client Report 2018248HN. Prepared for Marlborough District Council.

Busetto L, Ranghetti L. 2016. MODIStsp: an R package for automatic preprocessing of MODIS Land Products time series. Computers & Geosciences. 97:40–48. https://doi.org/10.1016/j.cageo.2016.08.020

Elvines D, Preece MA, Baxter A, Broekhuizen N, Ford R, Knight B, Schuckard R, Urlich SC. 2019. Best management practice guidelines for salmon farms in the Marlborough Sounds. Part 2: water quality standards and monitoring protocol (Version 1.0). Wellington: Ministry for Primary Industries. New Zealand Aquatic Environment and Biodiversity Report 230.

Gall MP, Pinkerton MH, Steinmetz T, Wood S. 2022. Satellite remote sensing of coastal water quality in New Zealand. New Zealand Journal of Marine and Freshwater Research. 56(3):585–616.

Helsel DR, Hirsch RM. 2002. Statistical methods in water resources. In: Techniques of water resources investigations. Book 4: Hydrologic analysis and interpretation. Reston (VA): United States Geological Survey; p. 65–93.

Hijmans R. 2023. raster: geographic data analysis and modeling. R package Version 3.6-20. https://CRAN.R-project.org/package=raster

Jiang W, Knight B, Cornelisen C. 2014. Application of remote sensing data to coastal monitoring of chlorophyll-*a*: case studies of locally calibrated empirical algorithms at coastal sites in New Zealand. Nelson: Cawthron Institute. Cawthron Report 2287.

Jiang W, Knight BR, Cornelisen C, Barter P, Kudela R. 2017. Simplifying Regional Tuning of MODIS algorithms for monitoring chlorophyll-*a* in coastal waters. Frontiers in Marine Science 4.

Knight B, Jiang W. 2014. Use of remote sensing to monitor water quality in Hawke Bay. Nelson: Cawthron Institute. Cawthron Report 2443. Prepared for Hawke's Bay Regional Council.

Knight B, Jiang W. 2018. Hawke's Bay coastal states and trends: analysis of fifteen years of remote sensing data. Nelson: Cawthron Institute. Cawthron Report 3189. Prepared for Hawke's Bay Regional Council.

Lee ZP, Carder KL, Arnone RA. 2002. Deriving inherent optical properties from water color: a multi-band quasi-analytical algorithm for optically deep waters. Applied Optics. 41:5755–5772.

Lee ZP, Lubac B, Werdell J, Arnone R. 2009. An update of the Quasi-Analytical Algorithm (QAA_v5). International Ocean Colour Coordinating Group. http://www.ioccg.org/groups/Software_OCA/QAA_v5.pdf

McBride GB. 2019. Has water quality improved or been maintained? A quantitative assessment procedure. Journal of Environmental Quality. 48(2): 412–420.

McLeod A. 2022. Kendall: Kendall rank correlation and Mann–Kendall trend test. R package Version 2.2.1. https://CRAN.R-project.org/package=Kendall

Morel A, Prieur L. 1977. Analysis of variations in ocean color. Limnology and Oceanography. 22(4):709–722.

Smith VH. 2006. Responses of estuarine and coastal marine phytoplankton to nitrogen and phosphorus enrichment. Limnology and Oceanography. 51(1):377–384.

Snelder T, Fraser C. 2019. The LWP-Trends Library: v2101 April 2021. Christchurch: LWP Ltd.

Sutton PJ, Bowen M. 2019. Ocean temperature change around New Zealand over the last 36 years. New Zealand Journal of Marine and Freshwater Research. 53(3):305–326.

Vermote EF, Roger JC, Ray JP. 2015. MODIS Surface Reflectance user's guide. Collection 6. MODIS Land Surface Reflectance Science Computing Facility. https://lpdaac.usgs.gov/documents/306/MOD09_User_Guide_V6.pdf

Zeldis JR, Howard-Williams C, Carter CM, Schiel DR. 2008. ENSO and riverine control of nutrient loading, phytoplankton biomass and mussel aquaculture yield in Pelorus Sound, New Zealand. Marine Ecology Progress Series. 371:131–142.