Cone Bay Barramundi Farm:

Benchmarking model performance against a long-term measured dataset

Final

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rev_a01	6/10/25	Draft report for client review	Dr Glenn R Shiell Joel Jebaratnam Jack Munns Joey Laugharne Emma Thillainath Jemima Dimbleby Dr Ru Somaweera Harrison Carmody Dr Louise Bruce Dr Gayan Gunaratne Amber Evans	Dr Glenn R Shiell Harrison Carmody Dr R Somaweera	Dr Glenn R Shiell Harrison Carmody Amber Evans Dr Gayan Gunaratne Dr Louise Bruce	T Schwinkowski

Author Contributions

This report was a collaborative effort between Stantec Pty Ltd and BMT Pty Ltd formed through a collective interest to bring greater rigor to aquaculture models applied in Western Australia. The main body of the report was prepared by GS and reviewed by GG, HC, LB and AE. The long-term data were compiled by JJ, JM, ET, JD and JL and analysed by JM and JJ. Model set up, execution, analysis and comparison with the measured data was undertaken by GG and LB. RS assisted GS with the preparation of the Discussion. The authors are indebted to the Marine and Freshwater Research Laboratory, Murdoch University, for supplying a proportion of the raw monitoring data needed for the analysis.

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Disclaimer

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List of Abbreviations

ANOVA – Analysis of Variance

BMT – British Maritime Technology

BOD – Biological Oxygen Demand

DIN – Dissolved Inorganic Nitrogen

DIP – Dissolved Inorganic Phosphorus

DO – Dissolved Oxygen

DoF – Department of Fisheries

EPA – Environmental Protection Authority

EP Act – Environmental Protection Act

EQC – Environmental Quality Criteria

EQO – Environmental Quality Objective

EQS – Environmental Quality Standard

EMMP – Environmental Monitoring and Management Plan

FCR – Feed Conversion Ratio

HEPA – High Ecological Protection Area

KADZ – Kimberley Aquaculture Development Zone

MaxEPA – Maximum Ecological Protection Area

MEPA – Moderate Ecological Protection Area

MPA – Marine Produce Australia

MS – Ministerial Statement

POC – Particulate Organic Carbon

PON – Particulate Organic Nitrogen

POP – Particulate Organic Phosphorus

PER – Public Environmental Review

PERMANOVA – Permutational Analysis of Variance

REF – Reference site

R&D – Research and Development

TOC – Total Organic Carbon

TN – Total Nitrogen

TP – Total Phosphorus

TSS – Total Suspended Solids

TUFLOW FV – Two-dimensional Unsteady FLOW Finite Volume

Executive Summary

Background

Tassal Group Ltd (Tassal) is seeking environmental approval under Section 38 of the Environmental Protection Act (EP) (1986) to establish up to seven new barramundi farms across the Buccaneer Archipelago. Presently, farming is limited to one site in Cone Bay where Tassal (formerly Marine Produce Australia) has been farming since 2003. Production volumes in the last 20 years have increased from <150 tonnes per annum (t/a) in 2003 to ~2,000 t/a in 2025. Under the new proposal, farming will be expanded to seven sites for a total annual production of 17,500 t.

Tassal's application under the EP Act was supported by the outcomes of comprehensive environmental model, comprising of integrated hydrodynamic, particle tracking, water quality and sediment diagenesis modules. The modelling aimed to predict the potential impacts of the proposed farms on the marine environment, and specifically, whether the proposal would meet the EPA's marine environmental objectives.

Modelling indicated there was potential for the farms to impart small changes to regional water quality, and moderate changes to sediments within the leases. A subsequent review by the EPA questioned the rigor of the model and whether its predictions were sufficiently conservative. In response, Tassal engaged Stantec and BMT to benchmark the performance of the model against long term measured data.

Approach

More than 136,000 data points were compiled from farm-affected and unaffected reference sites for key indicators comprising DIN, chlorophyll-a, DO, TP, and TOC%. The measured data were analysed using multifactorial ANOVA and time series methods. For the modelling component, BMT re-commissioned its model and used it to simulate the farming of approximately 1,700 t/a annum of barramundi, commensurate with production records for May 2020-May 2021. Results of the model were subsequently compared to the measured data for the same period, as well as data collected between 2003 and 2025.

Key Findings

- **Spatial Footprint**: Impacts from the existing farm in Cone Bay are highly transient and spatially constrained—typically 100–200 m for DIN and DO, and 10–200 m for TP—and are comparable to salmon farming benchmarks for low to moderate flow environments.
- **Model Conservatism**: The integrated model was highly conservative as expected, overpredicting chlorophyll-a, DIN, TP, and especially TOC%. The model also underpredicted the magnitude and the variability of DO, particularly near the pens.
- **Chlorophyll-a Trends**: Modelled outputs showed significant increases (up to 525%) in chlorophyll-a across parts of Cone Bay, while measured data indicated a steady-state system with no progressive increase since farming began—despite progressive increases in production from <150 t/a in 2003 to ~2000 t/a in 2025.

- **Waste Assimilation**: Variability in measured levels of TP and TOC% in the sediments suggests much of the accumulated solid waste is resuspended, mineralised and assimilated by phytoplankton—raising questions about the value of benthic monitoring in high flow, tropical environments.

Conclusions

The benchmarking study—the first of its kind applied to aquaculture models in Western Australia—offers new insights into the conservatism embedded in integrated aquaculture models and presents the first comprehensive analysis of the scale and magnitude of impacts from an existing barramundi farm, based on over 20 years of measured data.

The integrated model was highly conservative as expected, consistently overpredicting chlorophyll-a, DIN, TP, and especially TOC%. The model underpredicted the magnitude and the variability of DO, particularly near the pens. Modelling predicted a material increase in chlorophyll-a in response to farming, while the measured data reflected a stable environment with no changes in chlorophyll-a over a 20-year period, despite progressive increases in production. These data suggest the current production levels (circa 2,000 t/a) are within the carrying capacity of the Bay.

While integrated numerical models are mandated tools for aquaculture EIAs in Western Australia—including the Midwest and Kimberley Zones—this study has highlighted the importance of validating model predictions against long-term empirical data, when it is available. Validation exercises allow scientists and regulators to balance model conservatism with the most likely scenarios, using quantifiable processes and educated assumptions.

1 Introduction

1.1 Background

Tassal Group Ltd (Tassal) is seeking environmental approval under Section 38 of the Environmental Protection Act (EP) (1986) to establish up to seven new barramundi farms across the Buccaneer Archipelago. Presently, farming is limited to one site in Cone Bay where Tassal (formerly Marine Produce Australia) has been farming since 2003 (**Figure 2-1**). Production volumes in the last 20 years have increased from <150 tonnes per annum (t/a) in 2003 to ~2,000 t/a in 2025. Under the new proposal, farming will be expanded to seven new sites for a total annual production of 17,500 tonnes.

Tassal's application under EP Act was supported by the outcomes of comprehensive environmental model, comprising of integrated hydrodynamic, particle tracking, water quality and sediment diagenesis modules. The modelling aimed to predict the potential impacts of the proposed farms on the marine environment, and specifically, whether the proposal would meet the EPA's marine environmental objectives (see **Table 1-1**).

Table 1-1: The EPA's environmental factors and objectives.

Environmental Factor	Environmental Objective
Benthic Communities and Habitats	To maintain the structure, function, diversity, distribution, and viability of benthic habitats at local and regional scales.
Marine Environmental Quality	To maintain the quality of water, sediment, and biota so that the environmental values, both ecological and social, are protected.
Marine Fauna	To maintain the diversity, geographic distribution and viability of fauna at the species and population levels

Since 2012, the EPA has mandated calibrated integrated models for all finfish aquaculture EIAs in Western Australia, starting with the Kimberley Aquaculture Development Zone (KADZ), followed by the Midwest Zone in 2025, and most recently, the Ocean Barramundi Expansion Project (BEP). Both MWADZ and KADZ adopted highly conservative parameterisation—by underestimating hydraulic retention and overpredicting waste accumulation—to ensure precautionary outcomes, consistent with best practice standards. The BEP model followed this approach and, despite layered conservatism, indicated the proposal is broadly sustainable, with only worst-case scenarios potentially exceeding EPA's environmental quality guidelines. Under typical conditions, both EPA's environmental quality standards (EQSs) and objectives (EQOs) are expected to be met.

A subsequent review of the modelled outcomes by the EPA raised questions about the rigor of the model, and specifically, whether the model was sufficiently conservative in its predictions. Given the level of scrutiny applied to the model, Tassal engaged Stantec and BMT to benchmark the performance of the model against the long-term measured dataset.

This study is the first example of a model validation applied to aquaculture models developed for EIA purposes in Western Australia and brings a valuable new perspective on (a) the level of conservatism applied to the BEP model and (b) the impacts of current farming operations based on more than two decades of measured data.

1.2 Study Objective

The objective of this study was to benchmark the performance of the BEP model against the long-term measured data, collected beneath and adjacent to the existing farm. Specifically, the integrated model used for the BEP was re-commissioned and run over the 2020-21 period, in which Tassal produced roughly 1,700 tonnes of barramundi over a 12-month period. Results of the model were subsequently compared to the measured data for the same period as well as long-term data collected between 2003 and 2025.

2 Methods

2.1 Study Area

Cone Bay (16° 28’ 15.09” S, 123° 33’ 27.2” E) is a tropical marine embayment located in the macro-tidal Buccaneer Archipelago, ~215 km north-northeast of Broome, Western Australia (**Figure 2-1**). The Buccaneer Archipelago experiences daily water level fluctuations between 6 to 8 m, contributing to a highly dynamic environment. Minimum water depths in the Bay range from 0 m–41 m along two gradients: a west-east deep to shallow water gradient through the central axis of the Bay (21 m–5 m), with a separate and parallel deep-water channel between 10 m and 41 m depth between the mainland and Razor Island. The waters south of Razor Island and east of Turtle Island are relatively shallow at between 15 and 5 m depth. The shallowest regions are at the eastern end of the Bay which bifurcates to form two shallow mangrove lined water bodies of approximately 0–5 m depth.

MPA, and more recently Tassal, have been farming barramundi (*Lates calcarifer*) in Cone Bay (‘the Bay’) since 2003. Over that time, annual production has fluctuated between 150 and 2,000 t/a. The farming infrastructure consists of three grids of sea-pens, with each grid containing between seven and twelve pens of approximately 23 m diameter.

Mixing in the Bay is influenced by strong northly and southerly currents which sweep across the entrance of the Bay, forming a periodic anticlockwise eddy which effectively flushes the western half of the Bay every 12 hours (DHI 2013). In comparison, water movement in eastern Cone Bay (and particularly east of Turtle Island) is lower, leading to an environment characterised by lower grain sizes, higher productivity and organically enriched sediments (APASA 2006, DHI 2013, Oceanica 2013).

Mean current speeds in the Bay are low to moderate through the eastern and central ends of the Bay (0.62 m/s), and high to very high at the western end (0.80 m/s). Current speeds through the existing farms are low in comparison at between 0.25 and 0.45 m/s, due to the baffling effect of Turtle Island (DHI 2013, APASA 2006). Previous hydrodynamic modelling studies suggest that the direction of flow on the leeward side of Turtle Island, and into the embayments in the far east of the Bay, are easterly on incoming ‘flood’ tides and westerly on outgoing ‘ebb’ tides.

The embayment is bordered by granite cliffs and comprises a range of habitats from fringing coral reefs and coral rubble at the western end, to mangrove lined embayments characterised by soft sediments at the eastern end of the Bay (Brown & Root 2000, DHI 2013). Cone Bay experiences dry (April–October) and wet (November–March) austral seasons. The wet summer season generally experiences high humidity, regular heavy rainfall events, tropical cyclones and temperatures ranging from 26–34°C. The dry winter season is climatically more stable with light winds, extended sunny periods and cooler temperatures ranging from 18–24°C.

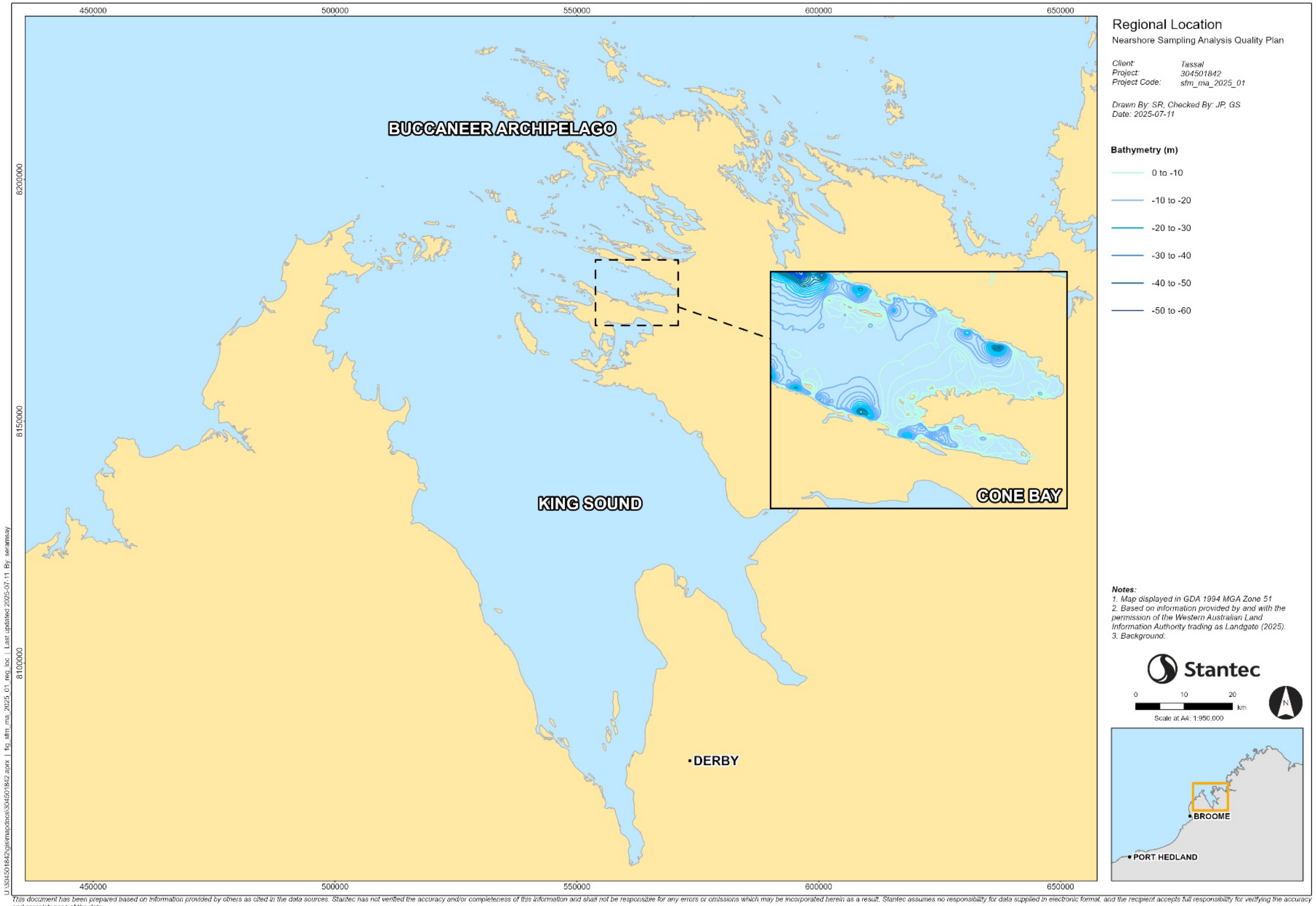

Figure 2-1: Location of Cone Bay relative to the Buccaneer Archipelago and King Sound.

2.2 Measured Estimates

2.2.1 Data Compilation

Tassal, and previously MPA, have collected environmental data in and around the Bay since 2003. These datasets, spanning more than two decades (2003–2025), consist primarily of the analytes listed in **Table 2-1**. Stantec compiled the dataset from raw data provided by Tassal and the Murdoch University Marine and Freshwater Research Laboratory (2006–2025), supplemented with data transcribed from historical reports covering 2003 to 2006 (Oceanica 2011; MPA 2010; Maxima 2008).

In total, the exercise resulted in the compilation and analysis of over 136,000 data points, comprising both farm affected (purportedly) (MEPA, HEPA and MaxEPA) and unaffected Reference sites (REF) (see **Section 2.2.2**). The value of these data is estimated at over $2.5 million in laboratory costs alone.

Table 2-1: Routine water and sediment quality parameters measured over a 21-year period between 2003 and 2025.

Routine Parameter	Metric
Sediment	• Total organic carbon (%C) • Total phosphorus (mg/kg) • Trace metals (Cu, Zn, Cd) (mg/kg)
Water	• Total and Volatile suspended solids (mg/L) • Dissolved Inorganic Nitrogen (mg/L) • Dissolved oxygen (% saturation) • Chlorophyll-a (ug/L)
Complimentary Parameter	**Metric**
Video observations	• Number of burrows (bioturbation) • Sediment colour • Observable farm waste • Observable outgassing (bubbles)

2.2.2 Spatial and Temporal Coverage

Despite the longevity of the dataset, the spatial and temporal design of monitoring has remained relatively consistent, facilitating a robust time series analysis.

- **2003–2012**: Sampling was undertaken at the cage edge (0 m; multiple replicates), 50 m and 200 m from the pens, with a single Reference site at the SE Pearl Lease.
- **2012–2025**: Monitoring was expanded to include additional sites downcurrent of the pens at 10 m and 100 m, as well as sites located at the HEPA and MaxEPA boundaries.
- **2003–2014**: Sampling frequency varied from monthly to several times per year, without a fixed seasonal schedule.
- **From 2014 onwards**: Sampling was standardised under the Environmental Monitoring and Management Plan (EMMP) for the Kimberley Aquaculture Development Zone (KADZ), required under MS 966. The EMMP prescribes approximately seven to eight sampling occasions annually, with four surveys conducted between December and March and four between June and September, thereby targeting the Austral wet and dry seasons.

Under the contemporary monitoring program (post 2014) (**Table 2-1**) sampling is conducted at a total of 18 sites: comprising: five Reference sites (REF) distributed through the centre of the Bay; five gradient sites (MEPA) extending 0 m, 10 m, 50 m, 100 m and 200 m from the central net pen cluster; and eight far-field sites (referred to respectively as HEPA and MaxEPA sites) located ~350 m and 850 m, from the easterly pen cluster (**Figure 2-2**).

Complementary data comprising measurements of infauna species diversity, together with qualitative observations of benthic conditions, were collected in August 2024 and March 2025 (**Table 2-1**). Infauna were sampled at a total of three Reference sites located at the eastern end of the Bay; fifteen gradient sites, comprising three replicate measurements at each of the 0 m-200 m distances; and eight far field sites, located ~350 m and 850 m, from the easterly pen cluster (**Figure 2-2**).

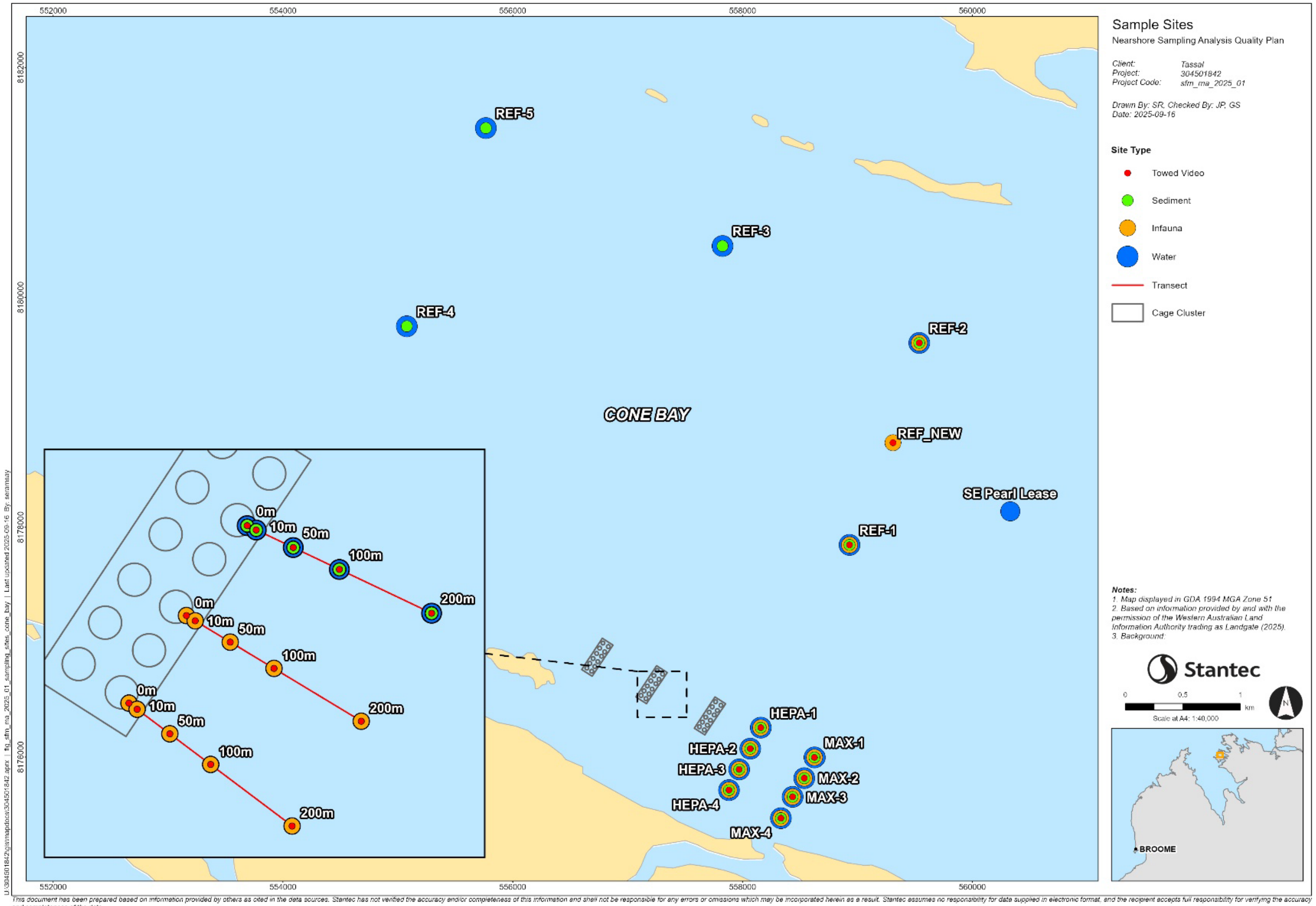

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Figure 2-2: Location of the routine and complementary sampling sites.

2.2.3 Statistical Analysis

The existing monitoring program design, while suitable for compliance purposes, presented numerous challenges for the statistical analysis:

1. First, Sites nested within Zones, while equal in number, were unevenly distributed in space, and as such did not meet the requirement for homogeneity of variance.
2. Second, the 20-year duration of the data spanned at least three major production periods: <200 tonnes, <1000 tonnes and <2000 t/a, relating respectively to the initial research and development (R&D) exemption period and the maximum levels of production allowable under Ministerial Statements 798 and 885. Within these periods, only the period between 2014 and 2025 contained suitable replication.
3. Third, the replicate measurements (0 m – 200 m) within one of the levels of Zone (i.e. MEPA) were exposed to different levels of farm pressure, and as such violated the assumption of independence.

To overcome the first constraint, the analyses were conducted using Permutational Analysis of Variance (PERMANOVA+), following Anderson et al. (2008). PERMANOVA allows for non-normality and is therefore considered a defensible tool for analysis of unbalanced designs.

The second constraint–relating to inadequate replication and differences in farming pressure, was resolved by restricting the analysis to the 2014-2025 period. This period also corresponded to farming production levels equivalent to roughly 2,000 t/a.

To overcome the third constraint of non-independence, the analyses proceeded using two mixed model designs: First, PERMANOVA+ (Anderson et al. 2008) was used to determine the extent of spatial and temporal differences in the data, by testing the relative importance of four main sources of variance:

1. Year (random factor with 11 levels [2014 to 2025]);
2. Season (fixed factor orthogonal to Year with two levels [wet and dry]);
3. Zone (fixed factor orthogonal to Season, with three levels [MEPA, HEPA, MaxEPA]); and
4. Site (random factor nested in Zone, with variable levels).

In this design, the replicates within the MEPA level of Zone were assumed to be independent, despite straddling the farm effects gradient. Similarly, the differences in variance due to the uneven spatial separation of the nested sites, were considered inconsequential.

Second, a separate PERMANOVA+ model was used to determine the spatial footprint of the farm relative to background values. A reduced model 3-factor design was used to test the relative importance of three main sources of variance:

1. Year (random factor with 11 levels [2014 to 2025]);
2. Season (fixed factor orthogonal to Year, with two [wet and dry]); and
3. Site (fixed factor, orthogonal to Season, with ten levels (0 m - 200 m, REF1 – REF 5).

In this design the challenges associated with the violation of independence and uneven spatial distribution were mitigated by eliminating Zone and elevating Site to a fixed factor, comprising of ten levels. Upon detecting a significant result ($p<0.05$), differences between the levels were elucidated using post hoc pairwise tests.

2.3 Modelled Estimates

2.3.1 Model Setup

For this study, BMT re-commissioned the integrated aquaculture model used to support the Ocean Barramundi Expansion Project (BMT 2025a). The model is the same integrated hydrodynamic, particle transport, water quality and sediment diagenesis model, as used in previous aquaculture EIAs including the Midwest Aquaculture Development Zone (BMT Oceanica 2016).

For the modelling exercise, BMT simulated the effect of an existing farm site near Turtle Island (**Figure 2-3**) in 2020-21 period using the same hydrodynamic, water quality and particle tracking parameterisation as applied in the previous Ocean Barramundi Expansion Project. In 2020-21, the combined sites yielded approximately 1,700 tonnes of barramundi at an average Feed Conversion Ratio of 2.3 (**Table 2-2**). Additional updates to the model included refinements to the mesh and the fish waste model, to (a) improve resolution around the farms and (b) ensure the model reflected farming outputs during the 2020-21 period. For further information on the integrated model setup, see BMT (2025a).

2.3.2 Modeled Outputs

Following its re-commissioning, the model was re-run between May 2020 and May 2021, capturing the Austral wet and dry seasons. Metabolic outputs from the farm including dissolved and solid nutrients were initially plotted as time series data 50^{th} percentiles, before being compared to the measured data from the same period. Water quality and sediment quality parameters, DO, DIN, chlorophyll-a, TP and TOC, were estimated using the TUFLOW FV water quality model as described in BMT (2025a). Concentrations of TP (mg/kg) and TOC (%C) in the sediment were back-calculated from the sediment diagenesis model (Paraska et al. 2015) using the assumed sediment bulk density and monthly depositional fluxes, as described below and summarized in **Table 2-3** and **Table 2-4** below.

TOC g/m^2 to TOC% Conversion

The TOC depositional footprint (g/m^2) was extracted at the end of the 12-month model run and divided by 12 to yield a monthly average. To calculate the TOC concentration as a percentage of benthic sediments, the simulated TOC footprint (g/m^2) was converted to TOC% using the sediment bulk density in a 0.05 m sediment depth before comparison with measured data.

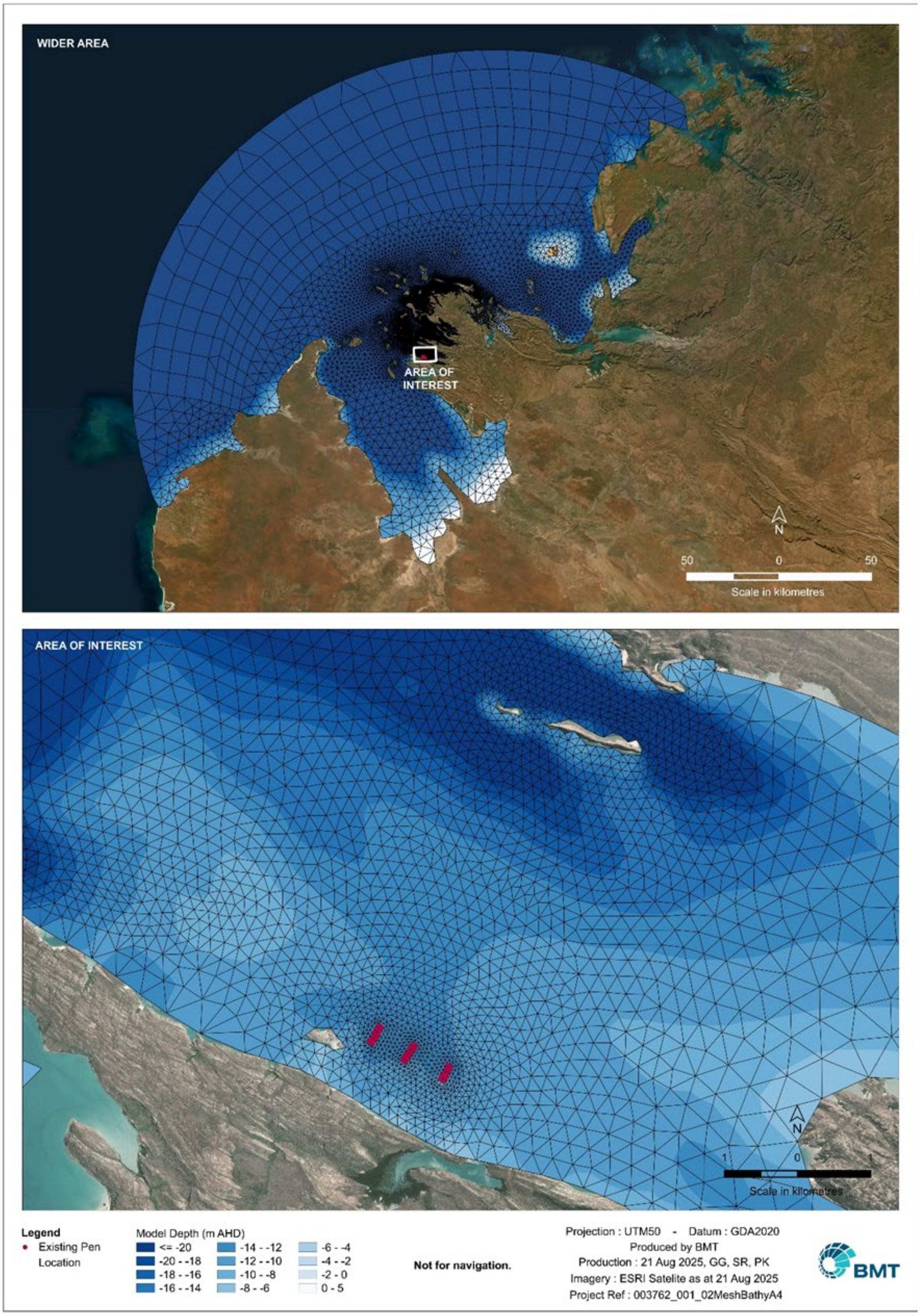

Figure 2-3: Extent and spatial resolution of the model applied to the present-day scenario for model validation purposes.

Table 2-2: Fish waste parameters for barramundi grown in Cone Bay.

Description		Parameter Name	Parameter Value	Units	Remarks	Data Source
Feed Conversion Ratio (FCR)			2.33			Tassal (2025a)
Farm Production			1,700	tonnes/annum		Tassal (2025a)
Biomass	Capacity	Net Standing Biomass per pen	195	tonnes	Based on maximum monthly pen biomass	Tassal (2025a)
Mass Balance	Input:	Feed Input Rate	0.21%	tonnes		Schipp et al. (2007), Tassal (2025a)
		Daily Feed Amount	0.370438	tonnes		Tassal, 2025a
	Output:	Metabolic Oxygen Demand	0.41	tonnes O_2/day	Based on 110.81% metabolic O_2 demand	BMT (2025a)
		C as CO_2	0.074		Based on 78% metabolic CO_2 rate	BMT (2025a)
		Total Waste Load	0.211	tonnes/day		
		Total Load C (T/day)	0.095	tonnes/day	Based on 45% C ratio in Feed	
		Total Excretion Load	0.211	tonnes/day	Based on 78% respiration	BMT (2025a)
Waste	Solid	Feed	0.00423	tonnes/day	Based on 2% Feed loss	
		Faecal 1	0.05181	tonnes/day	Based on 24.5% Feed to Faecal1	
		Faecal 2	0.06640	tonnes/day	Based on 31.4% Feed to Faecal1	
		Faecal 3	0.08902	tonnes/day	Based on 42.1% Feed to Faecal1	
	Dissolved	POC	0.02093	tonnes C/day	22% ration taken from Bermudes et al 2010	
		PON	0.00322	tonnes N/day	Based on SKA Barramundi grower - Nova FF-v10	
		POP	0.00279	tonnes P/day	Based on SKA Barramundi grower - Nova FF-v10	
		DIN	0.01752	tonnes N/day	Based on SKA Barramundi grower - Nova FF-v10	
		DIP	0.00120	tonnes P/day	Based on SKA Barramundi grower - Nova FF-v10	
		Total Carbon Loss	0.09515	tonnes C/day		
		Total Nitrogen Loss	0.02074	tonnes N/day		
		Total Phosphorus Loss	0.00399	tonnes P/day		

Table 2-3: Summary of steps used to calculate TOC% in the sediments from TOC flux.

Input values:

TOC = 100 g/m²

Bulk density = 1600 kg/m³ (Allis et al., 2019; van Rijn & Barth, 2018).

Sediment depth = 0.05 m (DoF 2014)

Step 1: Calculate sediment mass per unit area

$\text{Sediment mass per m}^2 = \text{Bulk density X Depth}$

$= 1600\ \text{kg/m}^3 \times 0.05\ \text{m} = 80\ \text{kg/m}^2$

Converting to grams:

$80\ \text{kg/m}^2 = 80{,}000\ \text{g/m}^2$

Step 2: Calculate TOC (%)

$$TOC\ (\%) = \left(\frac{TOC\ (\text{g/m}^2)}{Sediment\ mass\ (\text{g/m}^2))}\right) X100$$

$$= \left(\frac{100\ (\text{g/m}^2)}{80000\ (\text{g/m}^2))}\right) X100$$

$= 0.125\ \%$

TP calculation based on TOC% and fish waste model data

TP concentrations (mg/kg) in the top 0.05 m of sediment (mg/kg) were derived based on TOC % values and used the fish waste model stoichiometry to convert to TP. The method treated the Particulate Organic Carbon (POC) waste generated by the integrated aquaculture model as equivalent to the previously calculated sediment TOC and used a molar ratio based on barramundi aquaculture waste data to estimate phosphorus content. By converting TOC % to carbon mass and applying stoichiometric relationships, the method provides a practical and conservative estimate of TP levels in sediment, aiding in the evaluation of potential benthic impacts from aquaculture operations.

Table 2-4: Summary of steps used to calculate TP in the sediments from TOC flux.

At MEPA 0m location

TOC % = 2.73 % (by weight) (an 0.4 % background value was added to the model data)

TOC % = 2.73 %, which means 2.73 g of C per 100 g of material

Molar masses of carbon (C) and phosphorus (P):

Molar mass of C = 12.01 g/mol

Molar mass of P = 30.97 g/mol

$\text{Moles of C} = {}^{2.73\ \text{g}}/_{12.01\ \text{g/mol}}$

$= 0.227311\ mol$

POC: POP molar ratio = 1: 0.1, based on fish waste data, assuming all POC is TOC.

$$\text{Moles of P} = 0.227311 \text{ mol X } 0.1$$

$$= 0.0227311 \text{ mol}$$

$$\text{TP mass in 100g of sediment } = 0.0227311 \text{ mol X } 30.97 \text{ g/mol}$$

$$= 0.703981 \text{ g}$$

$$\text{TP mass in 1kg of sediment } = 7.03981 \text{ g}$$

$$= 7039.81 \text{ mg}$$

2.4 Validation Process

Model outputs for benthic and water column effects were compared against measured data collected during the same period, as well as the broader dataset (2014-2025). In addition, the median chlorophyll-a results from the production scenario (1,700 t/a) were compared with the modelled median baseline chlorophyll a values (no farming) to provide a semi-quantitative measure of the model's conservatism.

3 Results

3.1 Dissolved Inorganic Nitrogen (DIN)

The raw data presented in **Figure 3-1** show a variable farm signal characterised by intermittent spikes in DIN at sites located 0 m, 10 m, 50 m, and 100 m from the net pens (for values averaged by distance, see **Appendix B**). A 3-factor PERMANOVA detected significant differences among the 0 m, 10 m, and 50 m sites, but no significant differences between the 50 m and 200 m sites (**Table 3-1**, **Table 3-2**). These results indicate rapid dilution of farm-sourced nutrients within the first 50 m, followed by a more gradual decline with distance. Measurements at 200 m were comparable to background concentrations, suggesting the footprint of the farm (from the perspective of DIN) extends to a maximum distance of 100–200 m (**Table 3-2**).

Table 3-1: Results of a 3-factor mixed model PERMANOVA+ examining the effect of Year, Season and Site on DIN concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	898.76	4.3945	**0.0005***
Season	1	222.06	0.36331	ns
Site	9	1625.1	8.5089	**0.0001***
YearxSeason	10	660.88	3.2314	0.0028*
YearxSite	99	184.83	0.90372	ns
SeasonxSite	9	161.16	1.0243	ns
YearxSeasonxSite	90	151.58	0.74112	ns
Res	590	204.52		
Total	819			

Notes: Bold = terms of interest; NS = no statistical differences; * = significant result.

Table 3-2: Results of the post-hoc pairwise tests applied to the main effect of Site between 2014 and 2025.

		REF 1	REF 2	REF 3	REF 4	REF 5
a	MEPA 0 m	*	*	*	*	*
a,b	MEPA 10 m	*	*	*	*	*
b,c	MEPA 50 m	*	*	*	*	*
c	MEPA 100 m	*	*	*	*	*
c	MEPA 200 m	ns	ns	ns	ns	ns

Notes: ns = no statistical differences (p(perms)>0.05); * = significant result (p(perms) <0.05); MEPA sites with the same letter (i.e. a) are not significantly different from one another.

Further analysis using a 4-factor PERMANOVA found that on average DIN values in the MEPA differed significantly from the HEPA, MaxEPA and REF sites in some years, but not all years (**Table 3-3**). Similar results were obtained with respect to the effect of Season. While otherwise characterised by significant interannual variability, the results also pointed to occasional differences between seasons as indicated by the significant Year x Season interaction (**Table 3-3**).

Table 3-3: Results of a 4-factor mixed model PERMANOVA+ examining the effect of Year, Season and Zone on DIN concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	1611.8	13.054	**0.0001***
Season	1	53.143	0.14866	ns
Zone	3	3864.2	7.0467	**0.0001***
Site(Zone)	14	409.42	2.8686	0.0014*
YearxSeason	10	1048.7	9.1466	**0.0001***
YearxZone	33	219.67	1.779	**0.0141***
SeasonxZone	3	107.67	0.78276	**ns**
YearxSite(Zone)	154	123.48	0.6673	ns
SeasonxSite(Zone)	14	110.22	0.9011	ns
YearxSeasonxZone	30	177.14	1.545	ns
YearxSeasonxSite(Zone)	140	114.65	0.61959	ns
Res	1062	185.04		
Total	1475			

Notes: Bold = terms of interest; NS = no statistical differences; * = significant result.

Comparison of measured and modelled data showed the model underestimated the level of background dilution, resulting in inflated predictions over the first 200 m (**Figure 3-2**). The model also overestimated the length of the plume. While the analysis of the long-term data suggested a return to background conditions within 200 m of the pens (**Table 3-2**), thus constraining the footprint to the MEPA; the worst-case modelled outputs showed the plume traversed all three zones (MEPA, HEPA and MaxEPA) maintaining concentrations greater than background to at least 1,500 m (**Figure 3-2**).

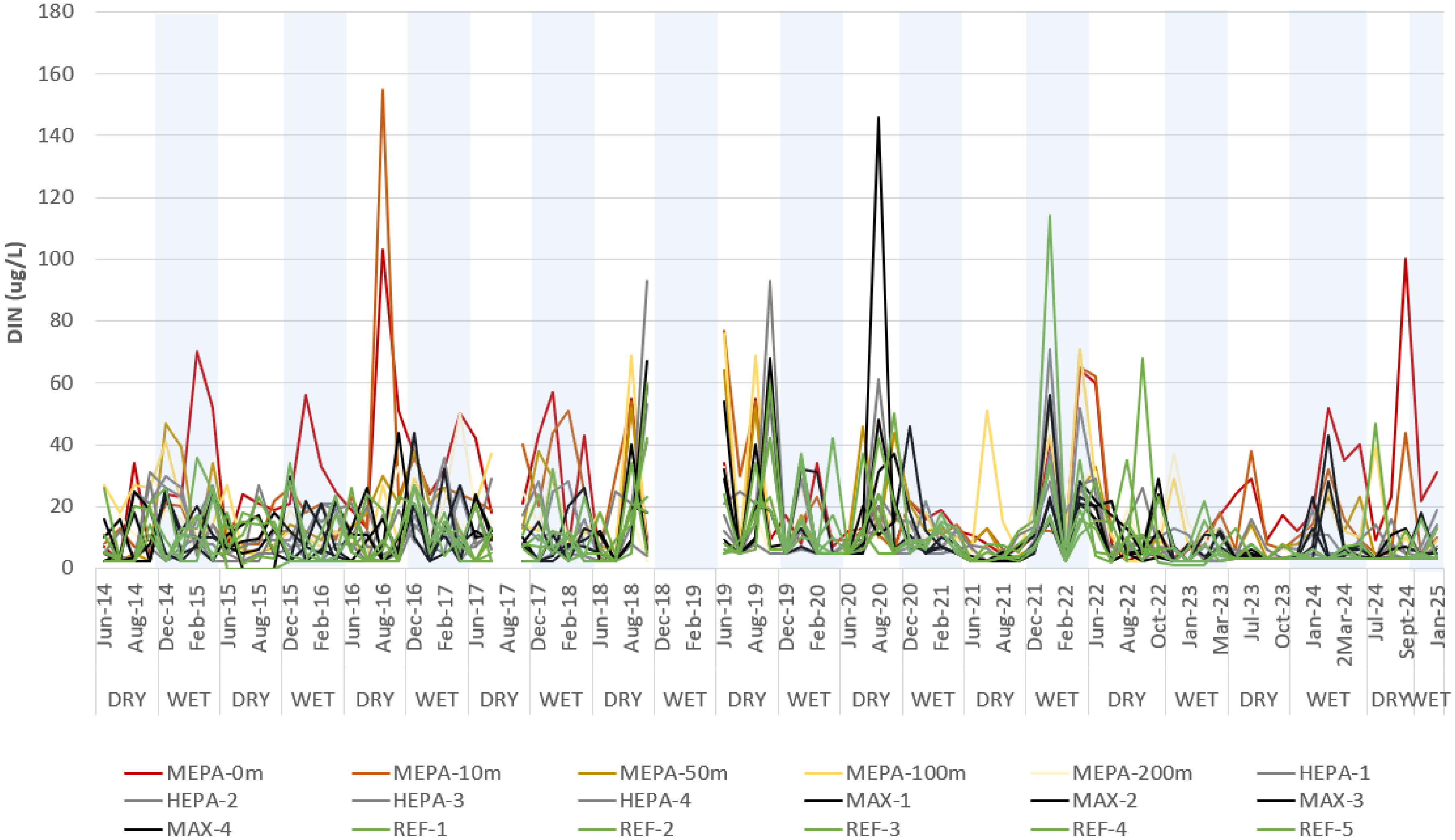

Figure 3-1: Time series data for DIN (µg/L) collected at sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

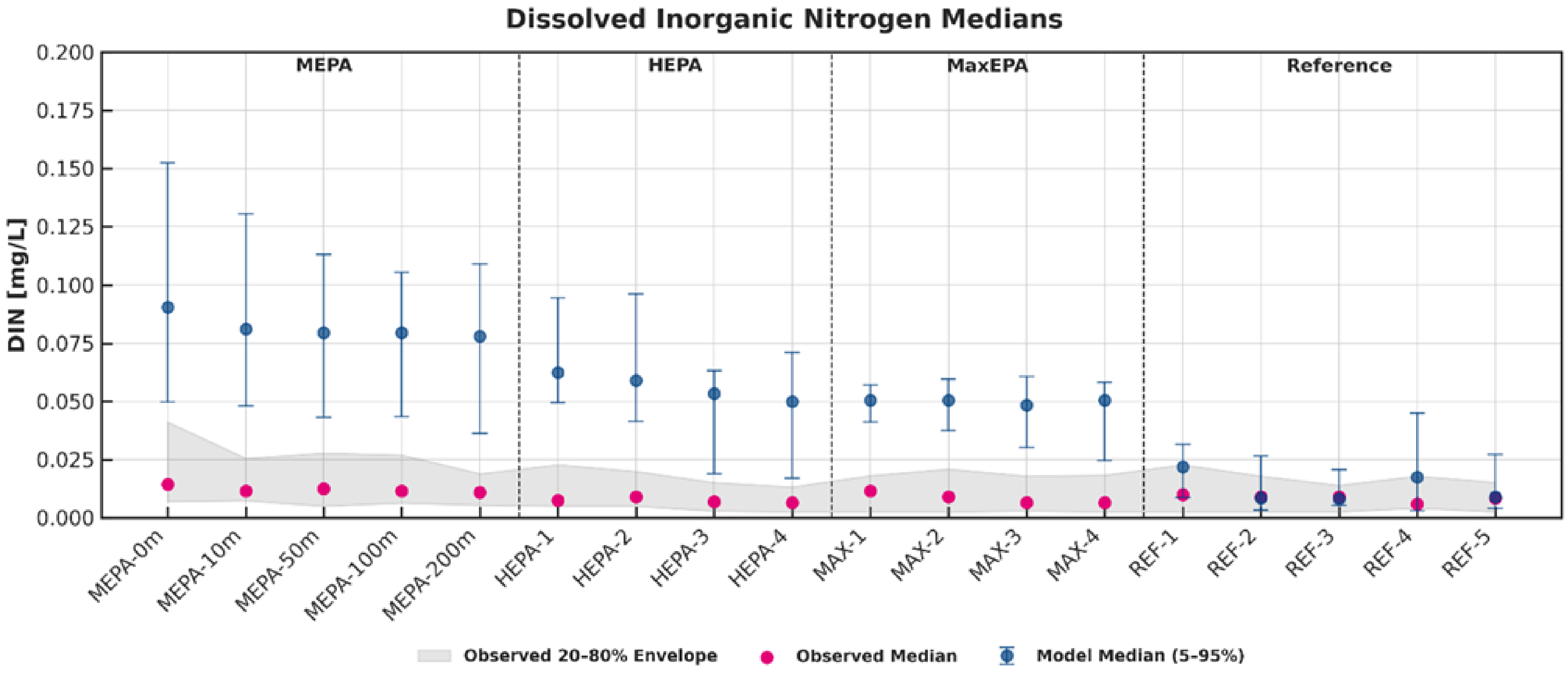

Figure 3-2: Modelled DIN concentrations relative to measured concentrations. Observed and modelled medians are for the 2020-21 period; observed 20-80% envelope is the range of values obtained over an 11-year period between 2014 and 2025.

3.2 Chlorophyll-a

Measured data demonstrated a clear spatial gradient with consistently elevated concentrations in the southeast corner of the Bay, averaging 1.12 µg/L in the HEPA zone and 1.0 µg/L in the MaxEPA zone, compared to lower concentrations in the central Bay REF zone which averaged 0.42 µg/L (**Figure 3-3**). Seasonal differences were also apparent, with values increasing from 0.77 µg/L in the dry season to 0.94 µg/L in the wet season (**Figure 3-3**).

Analysis using a 4-factor PERMANOVA found the significant result for the main effect of Zone was driven by lower values at the REF relative to the HEPA and MaxEPA sites, and the differences between levels of Season were restricted to the HEPA and MaxEPA sites (**Table 3-4**). Concentrations at the REF, by contrast, did not differ between seasons. These data, together with the results of the statistical analysis, suggest the southeast corner of the Bay is more variable and probably more productive than the centre of the Bay.

Table 3-4: Results of a 4-factor mixed model PERMANOVA+ examining the effect of Year, Season and Zone on chlorophyll-a concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	2.3672	47.394	**0.0001***
Season	1	5.8099	7.4949	**0.0029***
Zone	2	25.362	40.495	**0.0001***
Site(Zone)	10	0.18035	1.531	0.1388
YearxSeason	10	0.79083	11.628	**0.0001***
YearxZone	22	0.66529	13.32	**0.0001***
SeasonxZone	2	0.74633	3.1136	**0.0166***
YearxSite(Zone)	110	0.049948	0.1947	ns
SeasonxSite(Zone)	10	0.055711	0.671	0.7467
YearxSeasonxZone	20	0.22176	3.2608	**0.0001***
YearxSeasonxSite(Zone)	100	0.068008	0.2651	ns
Res	819	0.25654		
Total	1117			

Analysis of the time series data revealed a variable data set characterised by significant peaks in chlorophyll-a of up to 3.8 µg/L and troughs as low as 0.05 µg/L. As documented elsewhere (DHI 2019), algal blooms are common in the Bay and typically follow the first rain of the wet season. Blooms occur frequently in the eastern end of the Bay but only occasionally extend into the central region, as observed in 2019 and 2024.

Descriptive analysis using 50-day moving averages corroborated the presence of a strong spatial gradient in chlorophyll-a between the central and southern regions of the Bay. Separate analysis of time series data revealed a stable-state system with no evidence of a stepwise or gradual increase in chlorophyll-a since the beginning of production in 2003 or following increases in production in 2009 and 2014. The 50-day moving averages for the central and southern regions of the Bay instead appeared to remain steady over time, with no visible change in trajectory or variability (**Figure 3-3**) suggesting the gradient is of natural origin and driven by the hydrodynamics of the Bay.

Comparison of measured and modelled data confirmed the model is conservative. In the southern region of the Bay (HEPA and MaxEPA), most modelled estimates fell within the 20th–80th percentile of the long-term dataset, providing conservative yet reasonable predictions of measured concentrations. In contrast, model performance was materially more conservative in the centre of the Bay (i.e. REF), where the predictions diverged substantially from the observed values. Comparison of the modeled and measured data across the REF sites found the model overpredicted chlorophyll-a concentrations at 80% of the sites. The exception was at REF 4, where the predictions were closely aligned (**Figure 3-4**).

Comparison of the modelled baseline against the simulated 2020-21 production period (median values) demonstrated substantial differences in the modelled and measured environmental response (**Table 3-5**, **Figure 3-5**). Relative to the modelled baseline period, the model estimated that inputs of nutrients would result in a substantial increase in chlorophyll-a (**Figure 3-4)** throughout the southern, southeastern and northeastern parts of the Bay (200-525%), and a modest increase in the central region of the Bay (100-350%).

Table 3-5: Modelled estimates of chlorophyll-a under baseline and farming conditions.

Region	Modelled Baseline		Modelled Production (2000t/a)		% Difference
	Min (µg/L)	Max (µg/L)	Min (µg/L)	Max (µg/L)	
Central	0.2	0.6	0.4	2.7	100-350%
Southern	0.4	0.4	1.7	2.5	325-525%
North-Eastern	0.4	0.6	2.3	2.3	283-475%
South-Eastern	0.4	0.8	1.2	3.8	200-375%

In contrast, the measured data indicated a steady-state system, characterised by persistent spatial differences in chlorophyll-a (as shown in the baseline scenario, **Figure 3-3**), but with no evidence of stepwise or progressive increases since the onset of production in 2003, nor in response to farming at 2,000 t/a over the 2014–2025 period (**Figure 3-3**).

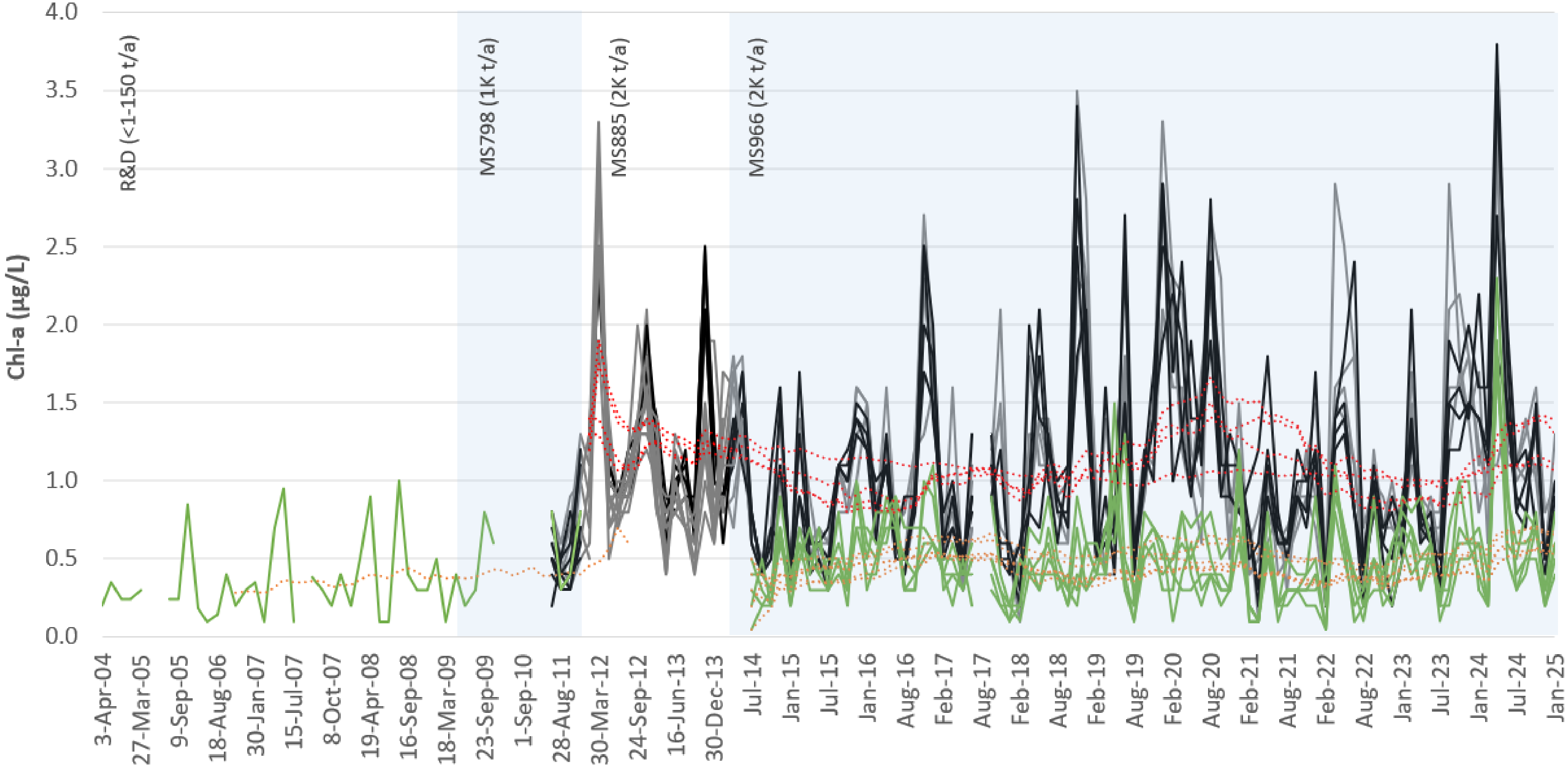

Figure 3-3: Time series chlorophyll-a (µg/L) collected at sites within the HEPA, MaxEPA and Reference Zones between 2004 and 2025. Green lines represent background conditions measured in the centre of the Bay; grey and black lines represent conditions in the HEPA and MaxEPA zones in the southern region of the Bay. Red dotted lines are the 15-point moving averages for the southern zone, and the orange dotted lines are the 15-point moving averages for the centre of the Bay. Production numbers are provided in parentheses.

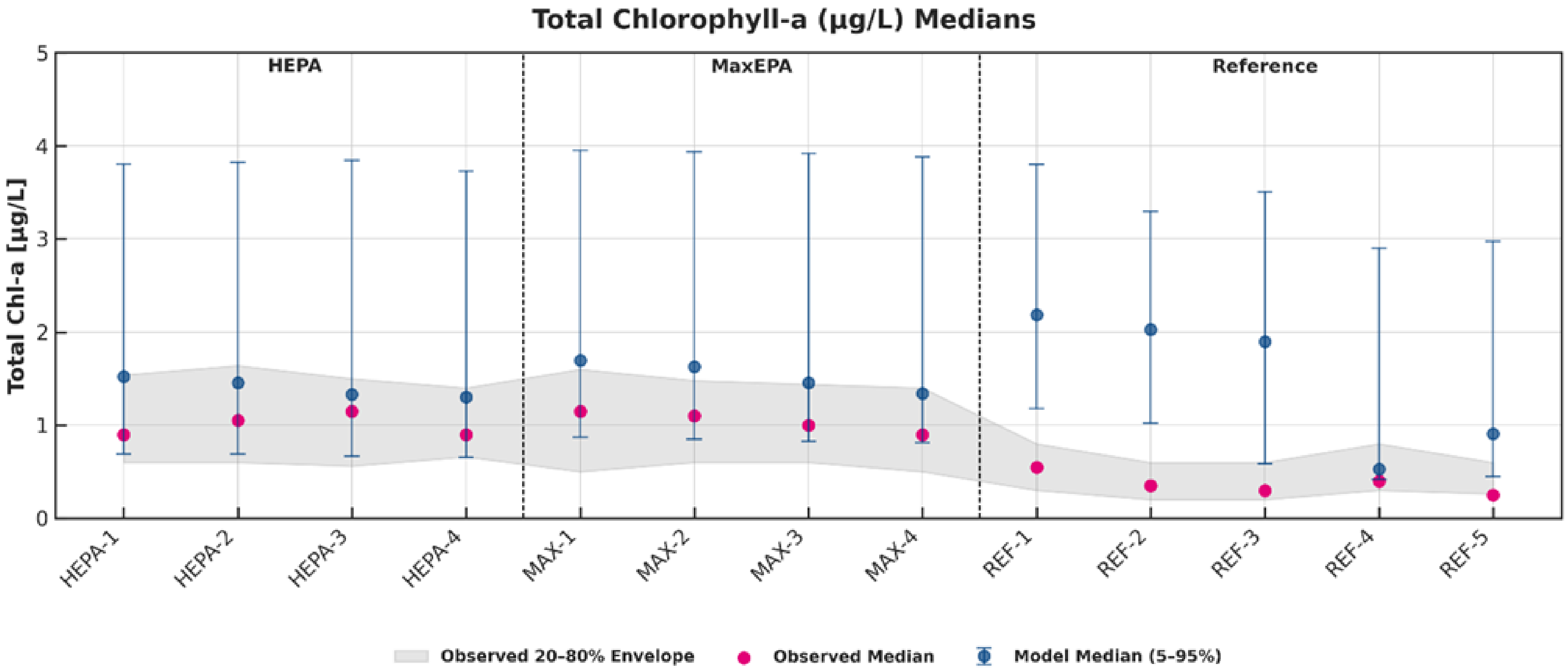

Figure 3-4: Modelled chlorophyll-a concentrations relative to measured concentrations. Observed and modelled medians are for the 2020-21 period; the observed 20-80% envelope is the range of values obtained over an 11-year period between 2014 and 2025.

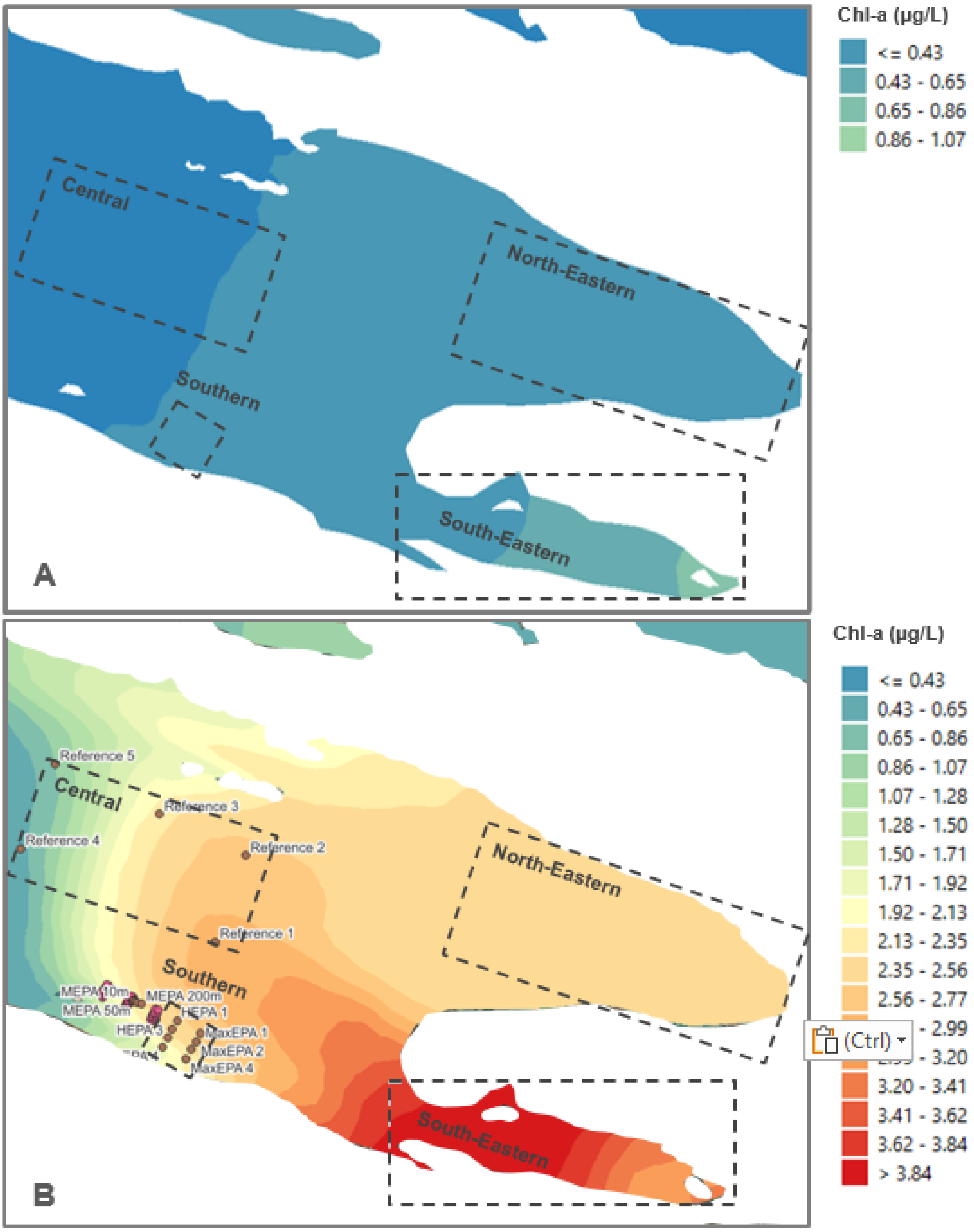

Figure 3-5: Modelled median chlorophyll-a concentrations under baseline (A) and 1,700 t/a production (B) in the 2020-21 period.

3.3 Dissolved Oxygen (DO)

The raw data presented in **Figure 3-6** are indicative of a dynamic system characterised by frequent, short-term variations in DO saturation with a tendency toward lower values in the MEPA. A significant interaction between Year and Zone in the 4-factor PERMANOVA supported this observation, confirming that while DO values in the MEPA were often lower than at the REF, such departures were itinerant and restricted to certain years (**Table 3-6**).

A 3-factor PERMANOVA detected significant differences in DO saturation between the 0 m (90.3 ± 10.4%) and 10 m (91.6 ± 9.5%) sites, but no significant differences among the 10 m, 50 m (92.8 ± 9.5%), 100 m (93.6 ± 8.8%), and 200 m (93.8 ± 9.0%) sites (**Table 3-7** and **Table 3-8**). Further analysis showed that DO saturation values at 0 m, 10 m, and 100 m differed consistently from those at the reference sites, while values at 50 m and 200 m differed approximately 80% of the time. Although not indicative of full recovery with distance, these results suggest that the most pronounced effects are consistently confined to within 50 m, with intermittent excursions extending to a maximum of 200 m.

On aggregate, these results confirm the presence of a significant down-current gradient in DO between the edge of the net pens and the sites further afield, indicative of a moderate anthropogenic effect. Although these reductions are likely attributable to biological oxygen demand (BOD) at the water–sediment interface, they were short-term, with conditions returning to background levels by the subsequent sampling event.

Table 3-6: Results of a 4-factor mixed model PERMANOVA+ examining the effect of Year, Season and Zone on DO concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	2100.6	127.83	**0.0001***
Season	1	55.812	0.11072	ns
Zone	3	914.43	8.1083	**0.0001***
Site(Zone)	14	48.502	1.1627	ns
YearxSeason	10	677.05	42.588	**0.0001***
YearxZone	33	96.696	5.8846	**0.0001***
SeasonxZone	3	83.158	1.3546	ns
YearxSite(Zone)	154	16.432	0.17264	ns
SeasonxSite(Zone)	14	6.8805	0.32328	ns
YearxSeasonxZone	30	70.216	4.4167	**0.0001***
YearxSeasonxSite(Zone)	140	15.898	0.16703	ns
Res	1134	95.18		
Total				

Notes: Bold = terms of interest; NS = no statistical differences; * = significant result.

Table 3-7: Results of a 3-factor mixed model PERMANOVA+ examining the effect of Year, Season and Site on DO concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	1051.5	12.673	0.0001*
Season	1	320.59	1.015	ns
Site	9	361.02	8.1997	0.0001*
YearxSeason	10	332.84	4.0113	0.0002*
YearxSite	99	25.634	0.30894	ns
SeasonxSite	9	13.209	0.40409	ns
YearxSeasonxSite	90	29.012	0.34965	ns
Res	629	82.975		
Total	858			

Notes: Bold = terms of interest; NS = no statistical differences; * = significant result.

Table 3-8: Results of the post-hoc pairwise tests applied to the main effect of Site between 2014 and 2025.

		REF 1	REF 2	REF 3	REF 4	REF 5
a	MEPA 0 m	*	*	*	*	*
a,b	MEPA 10 m	*	*	*	*	*
b	MEPA 50 m	ns	*	*	*	*
b	MEPA 100 m	*	*	*	*	*
b	MEPA 200 m	ns	*	*	*	*

Notes: ns = no statistical differences (p(perms)>0.05); * = significant result (p(perms) <0.05); MEPA sites with the same letter (i.e. a) are not significantly different from one another.

Further analysis showed the model overpredicted DO saturation by approximately 1–6% based on a comparison of the modelled and measured median values (**Figure 3-7**). The model also predicted a relatively narrow range of measurements of between 95% and 105% saturation, suggesting a relatively stable system (**Appendix A**). The measured data in contrast were indicative of a highly variable system with short-term deviations of +30% and – from the long-term median, to values as low as 48%-58% at 0-50 m within 50 m of the pens.

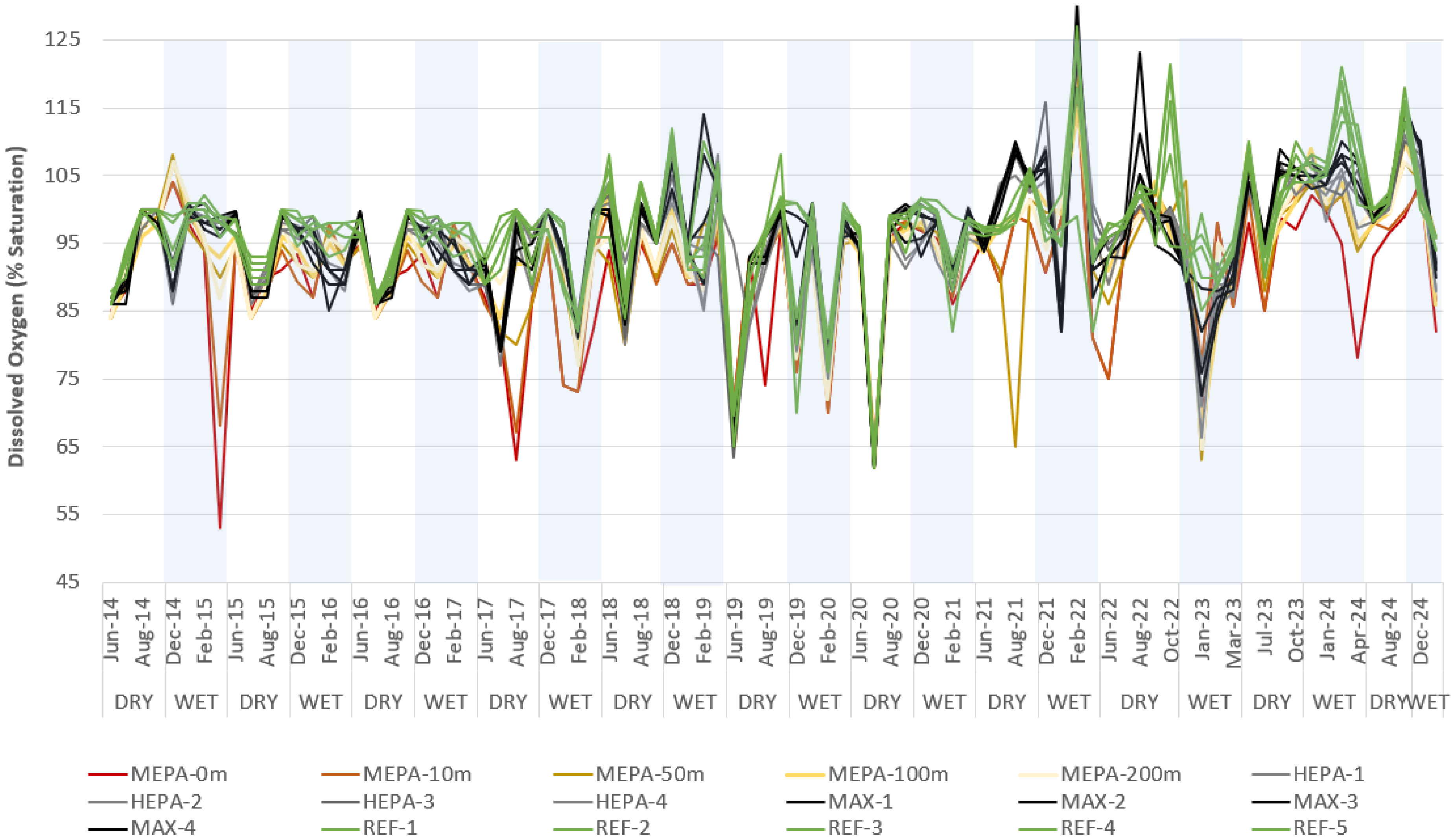

Figure 3-6: Time series data for DO% collected at sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

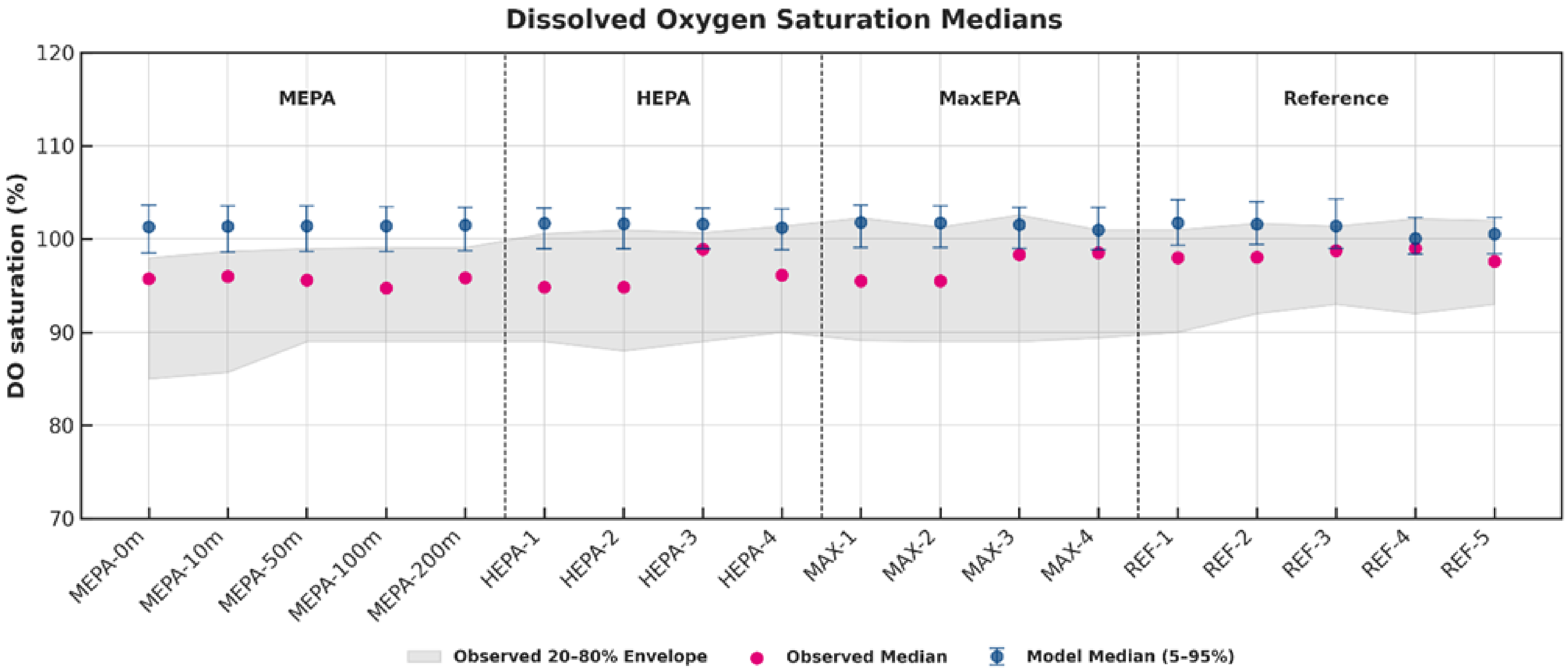

Figure 3-7: Modelled DO% relative to measured concentrations. Observed and modelled medians are for the 2020-21 period; the observed 20-80% envelope is the range of values obtained over an 11-year period between 2014 and 2025.

3.4 Total Phosphorus (TP)

Concentrations of total phosphorus in the sediments were variable between Years and Seasons but consistently elevated in the MEPA (924 ± 562 mg/kg) relative to the other Zones (417 ± 83 mg/kg) (**Figure 3-8**). Results of the 4-factor PERMANOVA testing for the effects of Year, Season and Zone found the differences between Zone and Season were dependent on Year (**Table 3-9**). Post hoc pair-wise tests confirmed the differences between Zones were significant in all years apart from 2018; while the significant differences between Seasons were restricted to 2017, 2021 and 2024.

The apparent decreasing gradient in TP between the leeward edge of the net-pens and the 200 m sites was tested using a separate 3-factor PERMANOVA. Results confirmed a pronounced concentration gradient, with TP concentrations highest directly beneath and adjacent to the net-pens (0 m: 1413 ± 1219 mg/kg; 10 m: 1166 ± 896 mg/kg) (**Table 3-10**). At these distances, TP concentrations were consistently elevated compared to the Reference sites (**Table 3-11**). At greater distances (50 m: 751 ± 322 mg/kg; 100 m: 697 ± 233 mg/kg; 200 m: 592 ± 142 mg/kg), TP concentrations were elevated on average but remained within the range of values measured at reference sites R2 and R3, aligning with background levels 20–40% of the time (**Table 3-11**). These data suggest the benthic footprint of the farm, as indicated by elevated concentrations of TP in the sediments, is restricted to a minimum radius of 10 m with occasional, yet highly variable excursions to a maximum distance of 200 m.

Table 3-9: Results of a 4-factor mixed model PERMANOVA+ examining the effect of Year, Season and Zone on total phosphorus concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	10	6.72E+05	3.179	**0.0025***
Season	1	7.14E+05	2.7861	**0.0478***
Zone	3	1.12E+07	6.3606	**0.0002***
Site(Zone)	14	1.55E+06	8.3549	0.0001
YearxSeason	9	2.16E+05	2.1126	**0.0374***
YearxZone	30	4.04E+05	1.9107	**0.0132***
SeasonxZone	3	2.98E+05	1.562	ns
YearxSite(Zone)	140	2.12E+05	1.5737	ns
SeasonxSite(Zone)	14	1.08E+05	1.0091	ns
YearxSeasonxZone	27	1.66E+05	1.6184	**0.0431**
YearxSeasonxSite(Zone)	124	1.02E+05	0.75901	ns
Res	875	1.35E+05		
Total	1250			

Analysis of the time series data between 2004 and 2025 revealed a highly variable data set characterised by irregular but short-lived spikes in TP, particularly at sites located between 0 and 50 m from the pens. The tendency toward occasional elevations at these distances varied little over time despite the increases in annual production from ~1,000 t/a in 2009 to over 2,000 t/a between 2014 and 2025. Of note however was the lack of a measurable footprint during the R&D phase (2003-2008) when annual production was less than 150 t/a.

Comparison of modelled and measured data revealed the model produced highly variable results, but on aggregate, was more conservative at the farm-affected sites (0–200 m) than at the REF sites (**Figure 3-9**). Despite its conservatism, the model accurately reproduced the trajectory of TP decline from 0 m to 200 m and correctly identified the distance at which concentrations approached background levels.

Table 3-10: Results of a 3-factor mixed model PERMANOVA+ examining the effect of Year, Season and Site on total phosphorus concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	1051.5	12.673	0.0001
Season	1	320.59	1.015	0.3252
Site	9	361.02	8.1997	0.0001
YearxSeason	10	332.84	4.0113	0.0002
YearxSite	99	25.634	0.30894	1
SeasonxSite	9	13.209	0.40409	0.9302
YearxSeasonxSite	90	29.012	0.34965	1
Res	629	82.975		
Total	858			

Table 3-11: Results of the post-hoc pairwise tests applied to the main effect of Site.

		REF 1	REF 2	REF 3	REF 4	REF 5
a	MEPA 0 m	*	*	*	*	*
a	MEPA 10 m	*	*	*	*	*
b	MEPA 50 m	*	ns	*	*	*
b,c	MEPA 100 m	*	ns	*	*	*
b,c	MEPA 200 m	*	ns	ns	*	*

Notes: ns = no statistical differences (p(perms)>0.05); * = significant result (p(perms) <0.05); MEPA sites with the same letter (i.e. a) are not significantly different from one another.

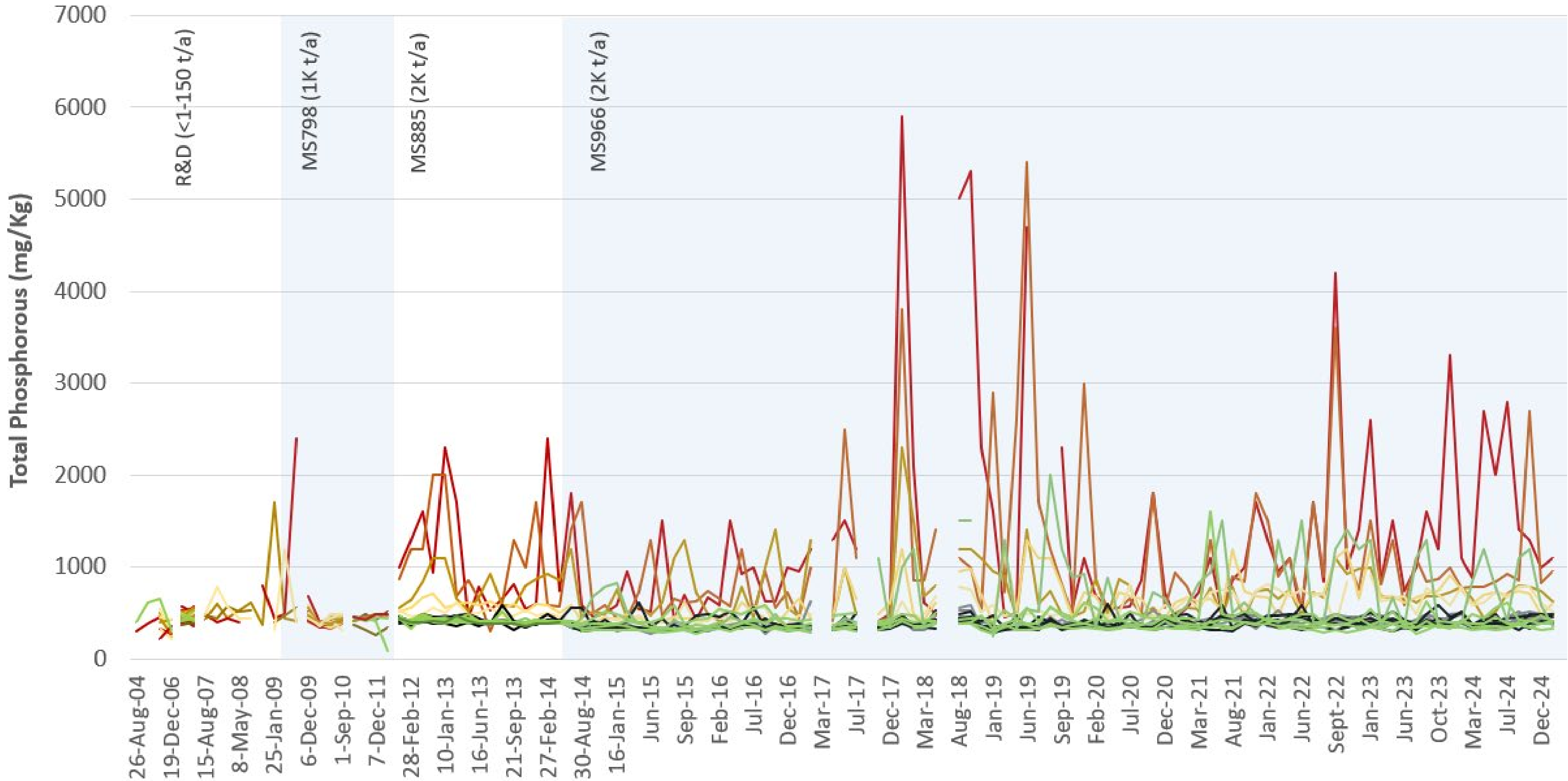

Figure 3-8: Time series data for TP (mg/kg) collected at sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2004 and 2024. Red, orange, brown, yellow and light-yellow lines represent sites located 0 m, 10 m, 50 m, 100 m and 200 m from the pens. Green lines represent background conditions measured in the centre of the Bay; grey and black lines represent conditions in the HEPA and MaxEPA zones in the southern region of the Bay.

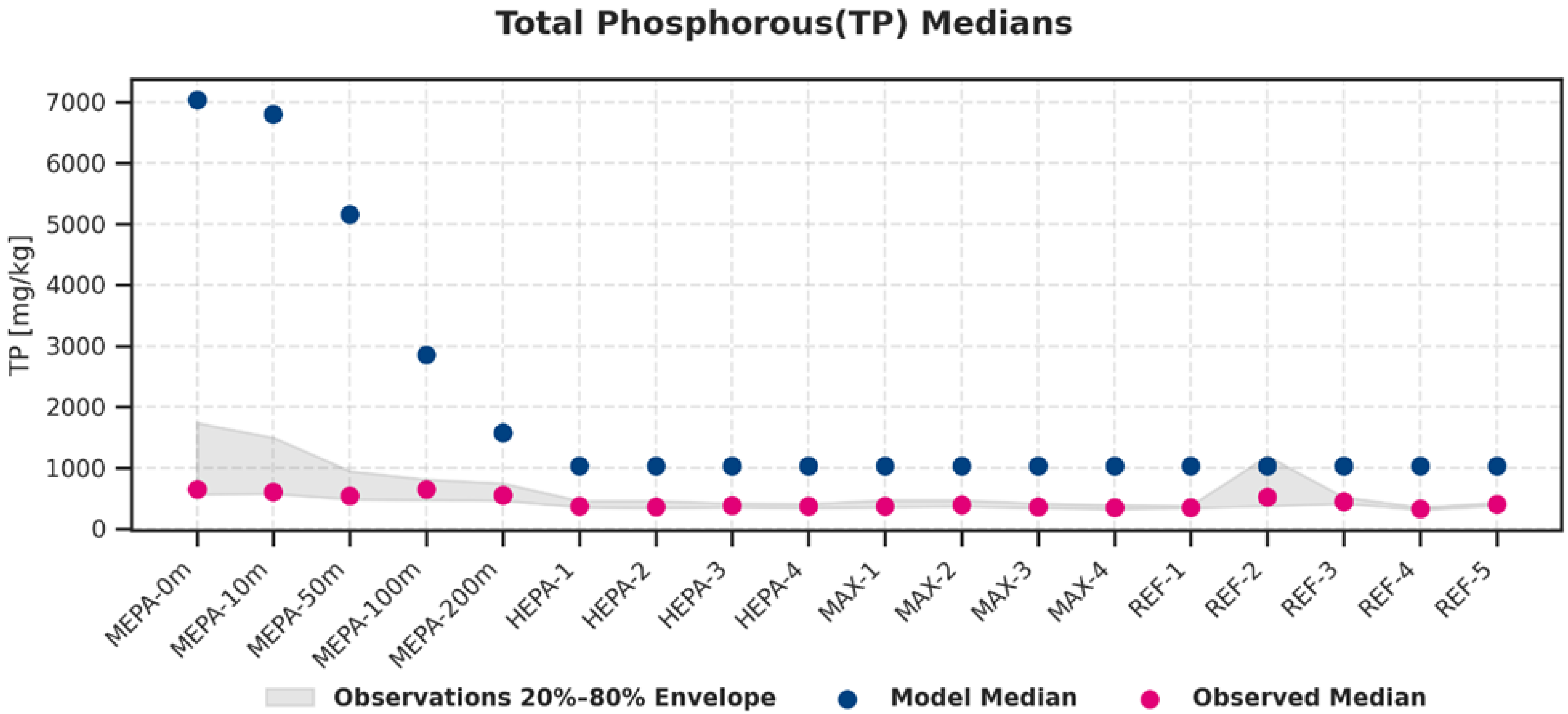

Figure 3-9: Modelled TP concentrations relative to measured concentrations. Observed and modelled medians are for the 2020-21 period; observed 20-80% envelope is the range of values obtained over an 11- year period between 2014 and 2025.

3.5 Total Organic Carbon (TOC)

Concentrations of TOC in the marine sediments were highly variable across Years, Season and Zone (**Figure 3-10**). The observed differences between Zones varied with Season and Year, but on average were highly significant (**Table 3-12**). A pair wise test conducted on the main effect of Zone confirmed the differences were driven by elevated levels at the HEPA and MaxEPA sites relative to the MEPA and REF sites. A subsequent 3-factor PERMANOVA was conducted to test the significance of the factor Site. Despite the tendency toward higher variability, and some evidence for elevated readings near the net pens, the differences between the sites closest to the pens and the reference sites were not significant (**Table 3-13**).

Table 3-12: Results of a 4-factor mixed model PERMANOVA+ examining the effect of Year, Season and Zone on TOC concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	0.74614	35.737	**0.0001***
Season	1	0.13231	0.25128	ns
Zone	3	2.6752	15.542	**0.0001***
Site(Zone)	14	0.14126	7.4011	**0.0001***
YearxSeason	10	0.61136	56.136	**0.0001***
YearxZone	33	0.047589	2.2793	**0.0002***
SeasonxZone	3	0.009019	0.69236	ns
YearxSite(Zone)	154	0.020879	1.3478	0.018
SeasonxSite(Zone)	14	0.004275	0.37964	ns
YearxSeasonxZone	30	0.025247	2.3182	**0.0005**
YearxSeasonxSite(Zone)	140	0.010891	0.70304	ns
Res	1152	0.015491		
Total	1565			

Table 3-13: Results of a 3-factor mixed model PERMANOVA+ examining the effect of Year, Season and Site on TOC concentrations between 2014 and 2025.

Source	df	MS	Pseudo-F	P(perm)
Year	11	0.24033	16.117	0.0001
Season	1	0.003661	0.015723	0.9147
Site	9	0.19463	12.096	0.0001
YearxSeason	10	0.25111	16.84	0.0001
YearxSite	99	0.016651	1.1167	0.2011
SeasonxSite	9	0.0061427	0.52416	0.8507
YearxSeasonxSite	90	0.011447	0.76766	0.9229
Res	601	0.014911		
Total	830			

With the exception of occasional elevated values in 2023 and 2024, TOC concentrations were consistently low, despite the recognised sensitivity of marine sediments to enrichment from net-pen aquaculture. Subsequent comparison of modelled and measured data showed the model overpredicted TOC concentrations within 200 m of the pens but underpredicted the naturally occurring concentrations in the southern region of the Bay (**Figure 3-11**). Concentrations at the other sites were otherwise well aligned.

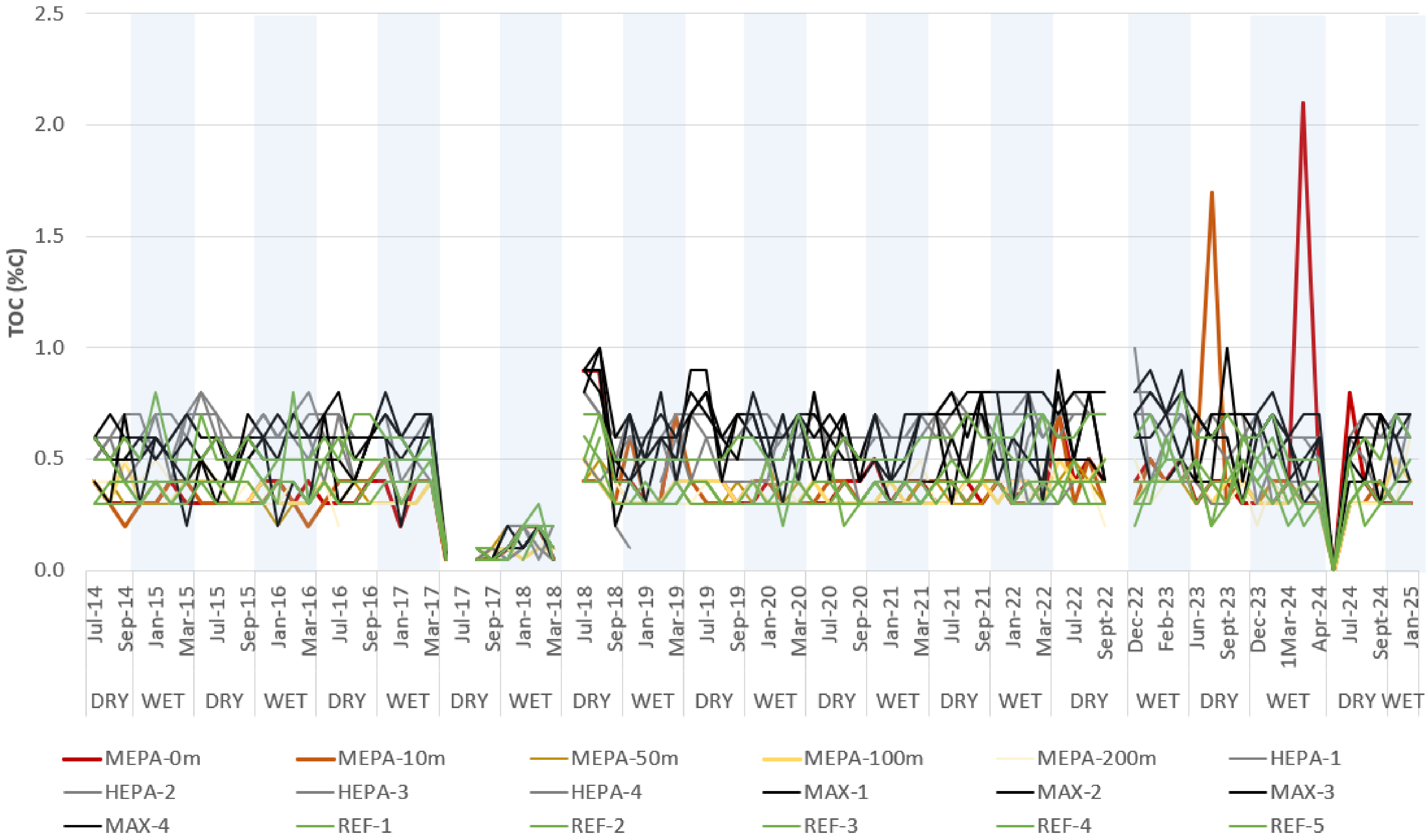

Figure 3-10: Time series data for TOC (%C) collected at sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

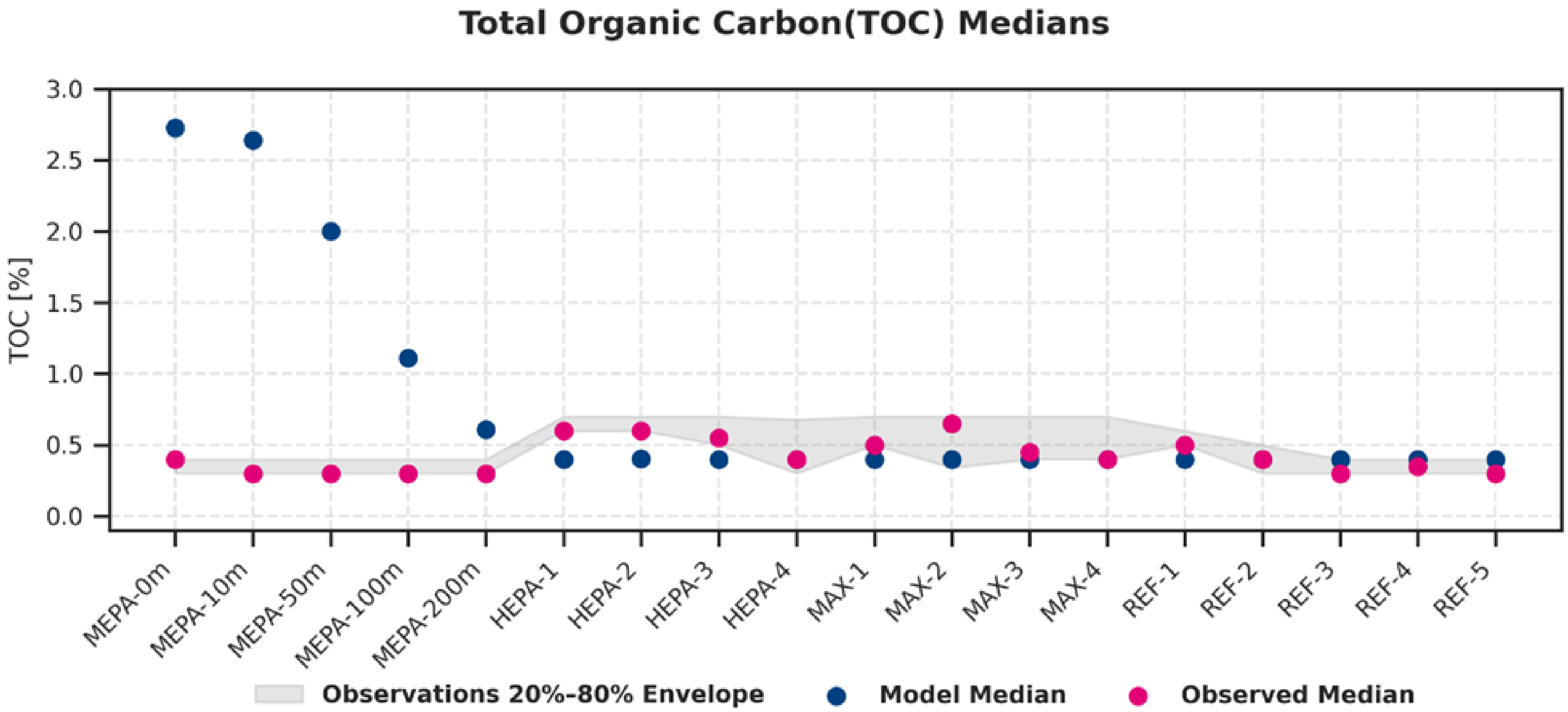

Figure 3-11: Modelled TOC% relative to measured concentrations. Observed and modelled medians are for the 2020-21 period; observed 20-80% envelope is the range of values obtained over an 11- year period between 2014 and 2025.

3.6 Visual Observations

Qualitative analysis of videos from August 2024 (dry season) showed a relatively uniform benthic habitat composed of fine- to coarse-grained sediments, with numerous burrows and widespread evidence of bioturbation. Observations included an unidentified fish species retreating into a burrow when approached by the camera. Other observations included generally poor visibility at most sites due to persistent levels of turbidity, and the scattered presence of macro-fauna including gorgonians and feather stars; the latter of which may be indicative of the presence of underlying hard substrata (**Figure 3-12**).

Evidence of farming was restricted to a thin veneer of dark-coloured material overlaying the seabed at two net-pen sites in August 2024 (i.e. 0 m) (see orange rimmed images in **Figure 3-12**). Agitation using the drop camera resulted in the resuspension of the material, suggesting it was organic in nature and limited to a superficial layer. The sediments beneath the material appeared lighter in colour, were pockmarked with burrows, and were similar in appearance to the sediments at the other sites. None of the sites revealed the presence of black or anoxic sediment, bacterial mats (e.g. *Beggiatoa* spp.), spontaneous outgassing or a material reduction in the number of burrows.

A subsequent visit during the wet season in March 2025 found no evidence of the dark-coloured material observed during the dry season of 2024. All material had since dissipated making way for a return to lighter-coloured sediments characterised by levels of bioturbation not dissimilar to the REF sites (**Figure 3-12**). The itinerant nature of the material is corroborated in the findings of sediment chemical analyses for TP (**Figure 3-8**), and perhaps DO (**Figure 3-6**), which points to a high degree of short-term temporal variability characterized by distinct spikes, followed by a return to background conditions on subsequent sampling events.

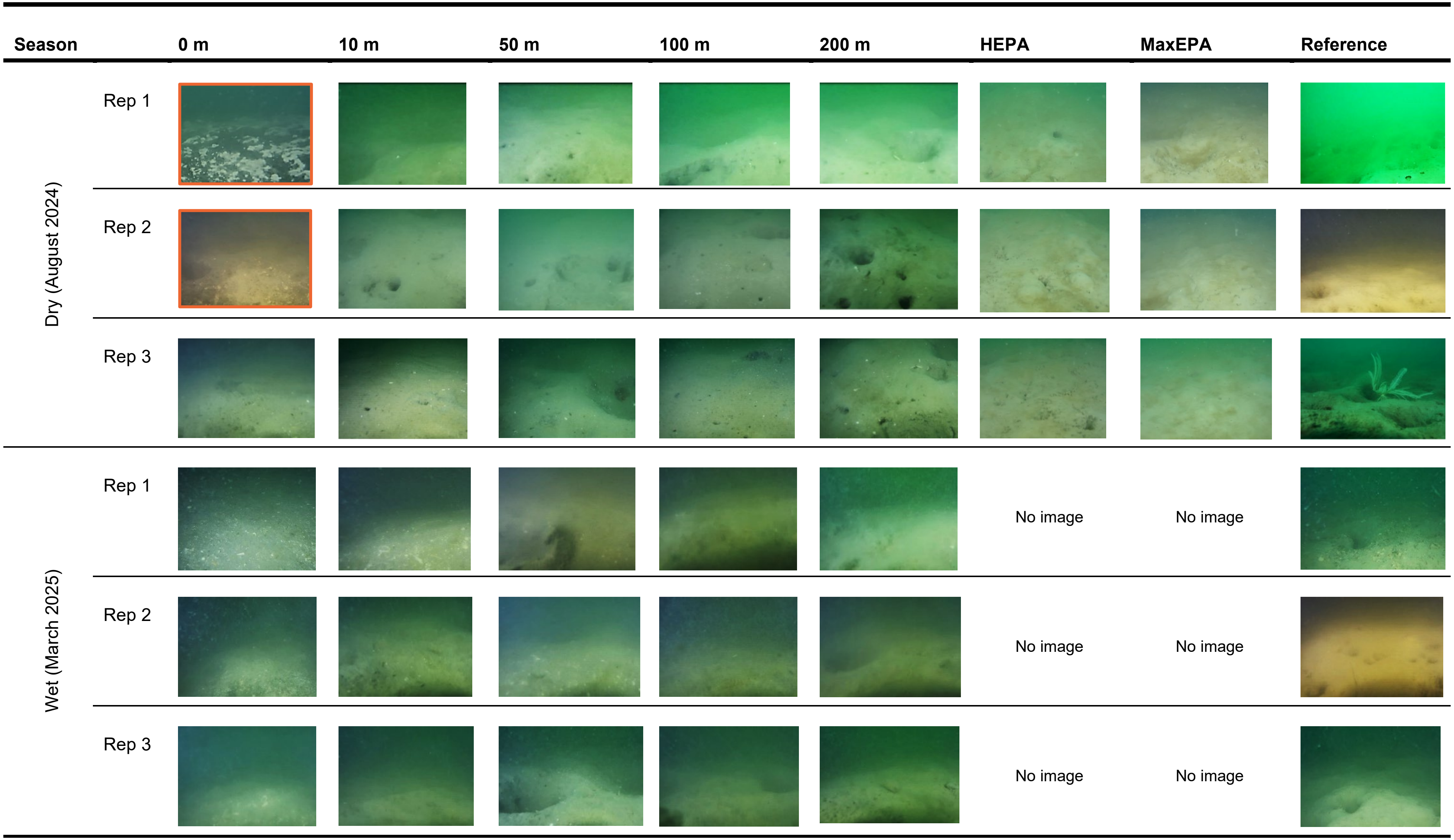

Figure 3-12: Representative imagery of the seafloor at the study sites in August 2024 and March 2025. Orange rimmed images denote visual evidence of farming activities.

4 Discussion

4.1 Model Validation Outcomes

The use of integrated models to assess environmental impacts from net-pen aquaculture in Western Australia dates back to 2012, beginning with the Kimberley Aquaculture Development Zone EIA, followed by the Midwest Zone in 2015, and most recently the Barramundi Expansion Project (BEP) in 2021–22. Although all models were calibrated with local hydrodynamic and water quality data, none have undergone retrospective validation. Model validation using measured data is rarely performed in aquaculture (but see Keeley et al. (2020) for examples applied to salmon farms). This study represents the first retrospective validation of a fish farm model in Western Australia, and the first documented validation for a tropical barramundi farm globally.

Most integrated aquaculture models applied to net pen aquaculture are designed to be highly conservative. Conservatism is a desirable quality driven by the application of the 'precautionary principle'; a concept which requires proponents to model the '*most likely best case*' and the '*most likely worst case*' scenarios, therefore accommodating for the inherent uncertainties in both model predictions and the complex response of the marine environment (Treeweek, 2003; Jeleva & Rossignol, 2029; EPA 2021).

Comparison of the modelled data with the measured data confirmed the model applied to the BEP is highly conservative, resulting in footprints considerably greater than measured. Estimates for TP, DIN and especially TOC were inflated relative to measured data. The results for chlorophyll-a were particularly compelling, with modelled outputs for the existing farm (1,700 t/a production) leading to a material change in chlorophyll-a in response to farming, at a scale that varied between the western and eastern ends of the embayment. Measured data by contrast revealed a steady-state system with no evidence of a sustained increase in chlorophyll-a since the beginning of farming in 2003 nor following progressive increases in production between 2006 and 2025.

4.2 Measured Data Outcomes

Results presented here further our understanding of the impacts of net-pen aquaculture in highly dynamic, tropical marine environments. Measured data from 2003 to 2025 revealed that the farm-related signal is itinerant and spatially limited—typically extending ~100–200 m for dissolved inorganic nitrogen (DIN), 200 m for dissolved oxygen (DO), and 10–200 m for sedimentary solid wastes. Footprints of this nature are consistent with those reported near salmon farms under low to moderate flow regimes, where effects were observed to dissipate within 100–200 m (Brooks & Mahnken 2003; Borja et al. 2009; Papageorgiou et al., 2010). By contrast, studies in highly dynamic system in Norwegian fjords have measured impacts up to 1 km from fish farms (Kutti et al. 2007; Keeley et al. 2019). Data presented here suggest the environment beneath and adjacent the existing farm site is subjected to frequent 'resetting events', whereby DO levels and TP concentrations in the sediments—although periodically deflated and elevated respectively—were often observed to return to background levels by the following sampling event.

This notion was corroborated by the drop camera observations, which revealed a well-flushed environment comprising coarse to silty sediment with extensive bioturbation. Repeated observations found that visual signals from farming were itinerant and spatially confined to one of three net pen sites

(0m). Subsequent observations three months later revealed the sediments had returned to baseline conditions, comprising clean sediments with no visible evidence of organic material.

The visual observations—although limited to two occasions—were counter to the measured chemical footprint which in the case of TP extended 200 m from the pens (**Figure 3-8**). Keeley et al. (2019) reported similar findings at a dynamic site in Norway, where despite the measured changes in sediment chemistry, the seabed remained visibly unimpacted. These results underscore the potential for ambiguity and demonstrate the potential disconnect between visual observations and the actual biological and geochemical condition of the seabed.

Findings from this study and previous work (DHI 2013; BMT Oceanica 2016; BMT 2024) confirmed the presence of a natural environmental gradient between the eastern and western ends of the Bay. Similar cross-shelf patterns have been observed in Strickland and Collier Bays, with higher productivity in shallow inshore areas than in deeper channels and reef passes. While the local biogeochemistry is still largely unresolved, research shows the cross-shelf gradients are characterized by unique microbial communities adapted to spatial light gradients and seasonal nutrient shifts. For aquaculture, this highlights the importance of managing embayments separately from deeper shelf waters, especially where farms are sited in zones with greater hydraulic retention times. The hydrodynamics of Cone Bay and the Buccaneer Archipelago in general also underscore the need for careful site selection for compliance monitoring purposes. Poorly chosen reference sites may lead to false exceedances of trigger criteria, risking the proponent's regulatory and social licenses.

One of the more profound findings of this study was the variability of the signals for TP as well as the general absence of TOC in the sediments immediately beneath the farms. The absence of TOC beneath the pens was surprising given the widely held notion that net-pen farming leads to significant organic enrichment particularly in poorly flushed environments. Organic carbon forms a significant component of fish faecal waste and its absence in Cone Bay suggests the material is either frequently resuspended (and washed away) or rapidly mineralised, or both. In dynamic environments, mineralisation converts the solid organic nutrients in the fish waste to dissolved bioavailable form within 160 hours at 10 °C. Given Cone Bay's warmer temperatures (18–31 °C), much of the accumulated solid waste may instead be mineralised and assimilated by phytoplankton within a fraction of the time observed elsewhere. This poses an interesting theoretical conundrum that the focus on benthic impacts in the monitoring–although commonly applied under best practice–is potentially redundant in high flow, warm water environments where the effects of farming are probably best monitored as changes in chlorophyll-a relative to baseline.

5 Conclusions

The benchmarking study—the first of its kind applied to aquaculture models in Western Australia—offers new insights into the conservatism embedded in integrated aquaculture models and presents the first comprehensive analysis of the scale and magnitude of impacts from an existing barramundi farm, based on over 20 years of measured data.

Impacts from the existing farm in Cone Bay are highly transient and spatially constrained—typically extending 100–200 m for DIN and DO, and 10–200 m for TP. These data are the first of their kind for an ocean-based barramundi farm globally and are comparable to salmon farming benchmarks for low to moderate flow environments in the Northern Hemisphere.

The integrated model was highly conservative as expected, consistently overpredicting chlorophyll-a, DIN, TP, and especially TOC%. The model also underpredicted the magnitude and the variability of DO, particularly near the pens. Modelled outputs showed significant increases (100-525%) in chlorophyll-a across parts of Cone Bay in response to farming, while measured data indicated a steady-state system with no progressive increases in chlorophyll-a since 2003, despite progressive increases in annual production from <150 t/a in 2005 to ~2000 t/a in 2025. These data suggest that current farming production levels (circa 2,000 t/a) are within the carrying capacity of the Bay.

While integrated numerical models are mandated tools for aquaculture EIAs in Western Australia—including the Midwest and Kimberley Zones—this study has highlighted the importance of validating model predictions against long-term empirical data, when it is available. Validation exercises allow scientists and regulators to balance model conservatism with the most likely scenarios, using quantifiable processes and educated assumptions.

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Appendices

Appendix A Supplementary Modelling Outputs

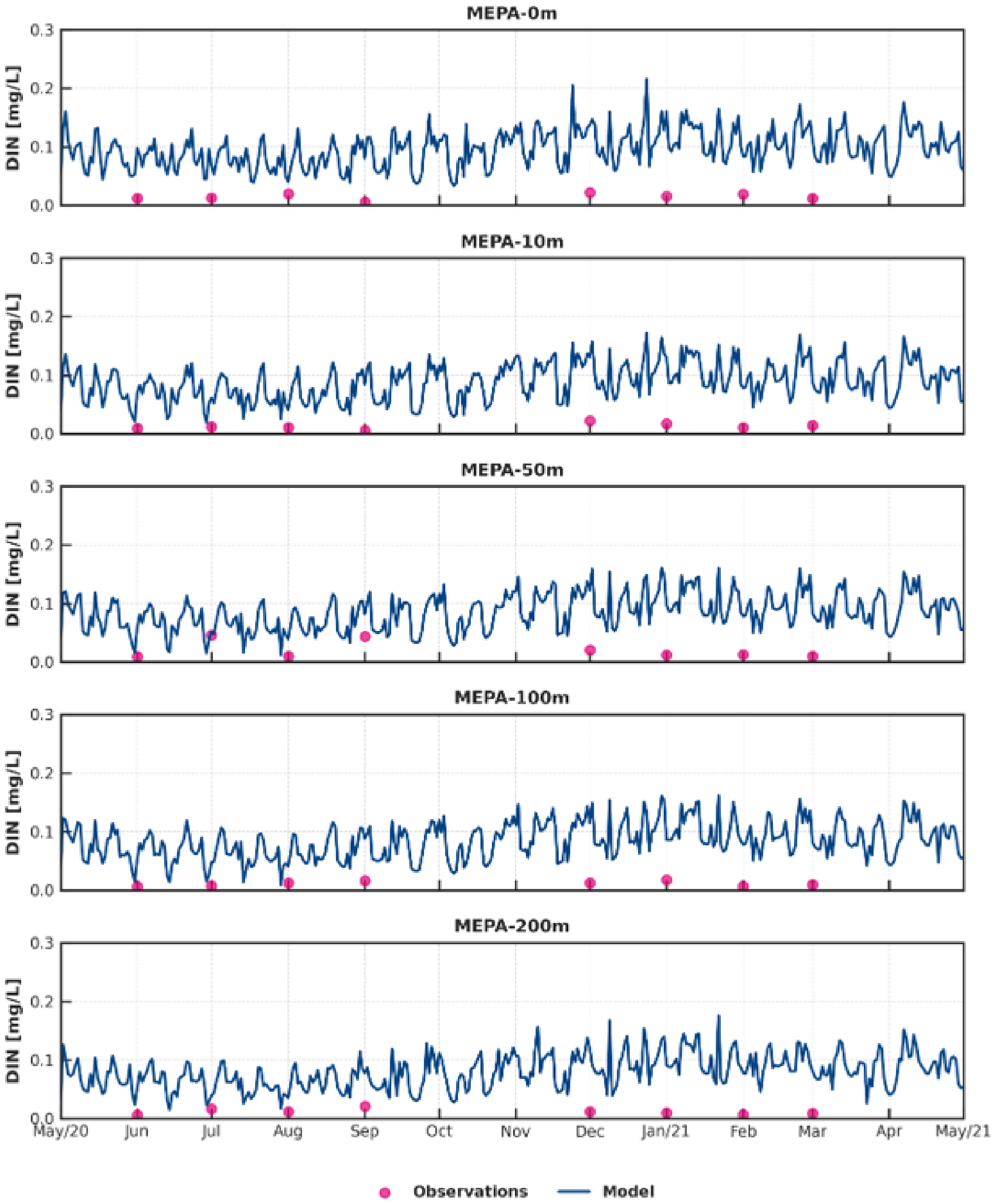


Figure A1: Time series of near surface model and observed data for DIN concentrations in mg/L at MEPA locations for the model period.

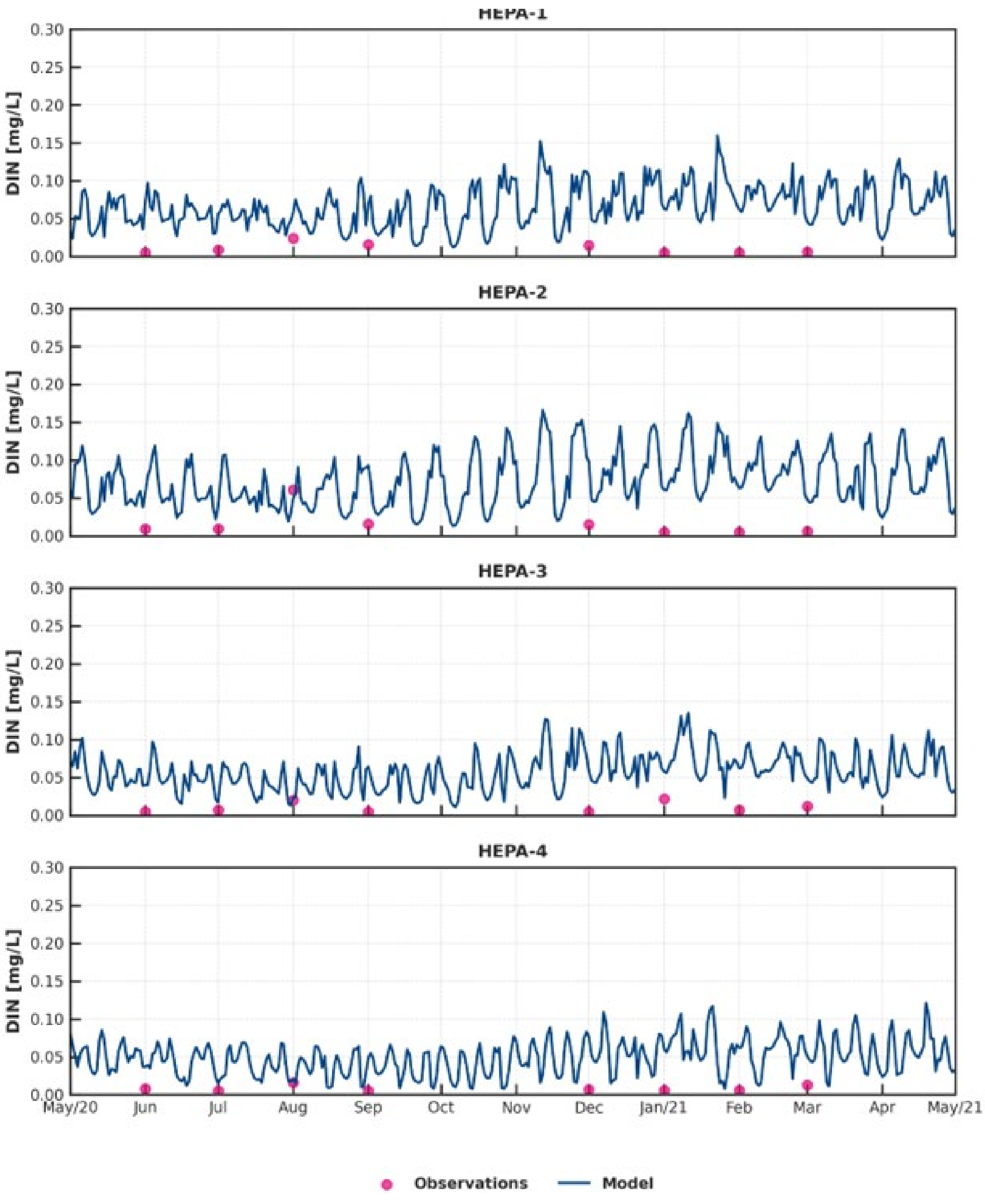


Figure A2: Time series of near surface model and observed data for DIN concentrations in mg/L at HEPA locations for the model period.

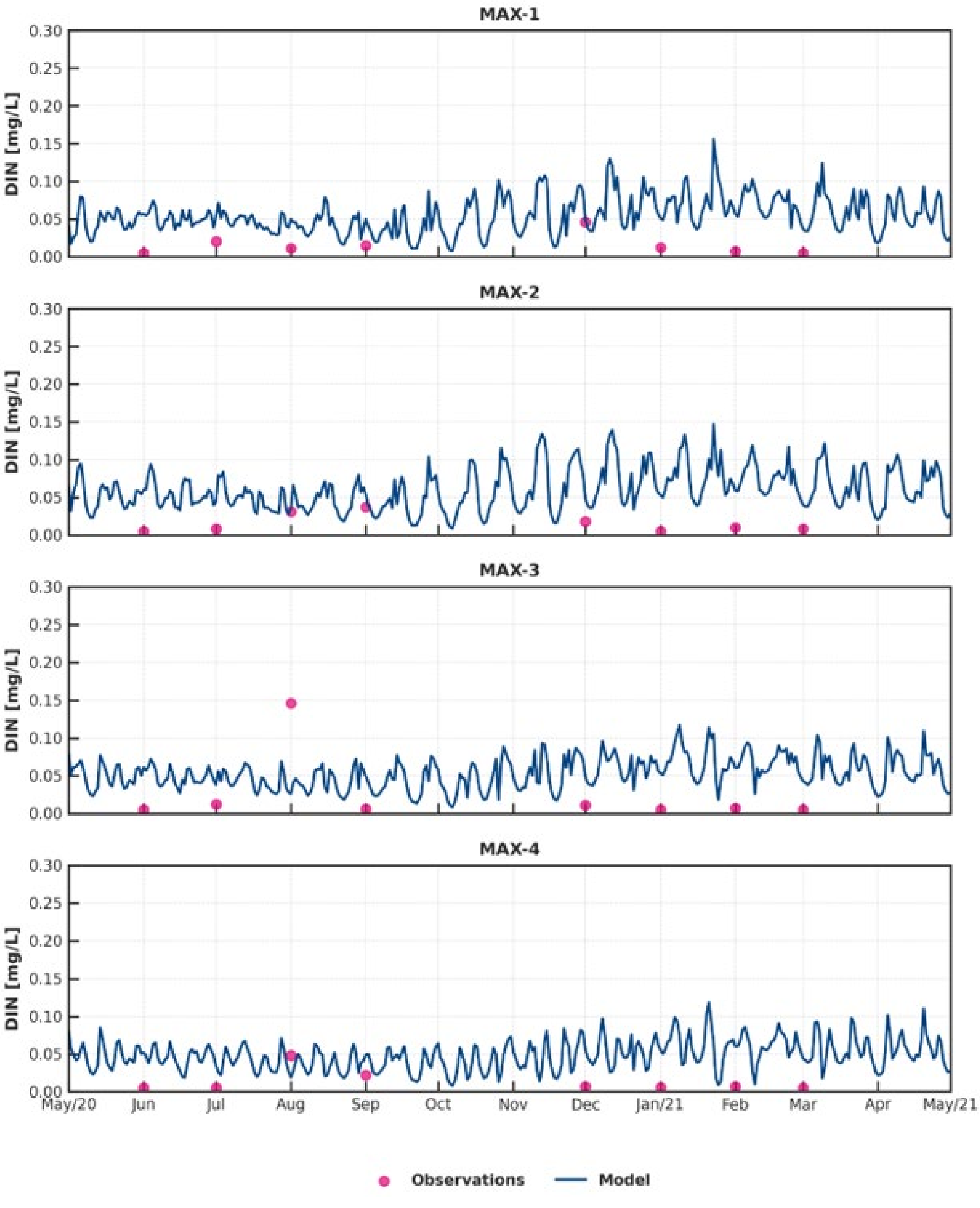


Figure A3: Time series of near surface model and observed data for DIN concentrations in mg/L at Max-EPA locations for the model period

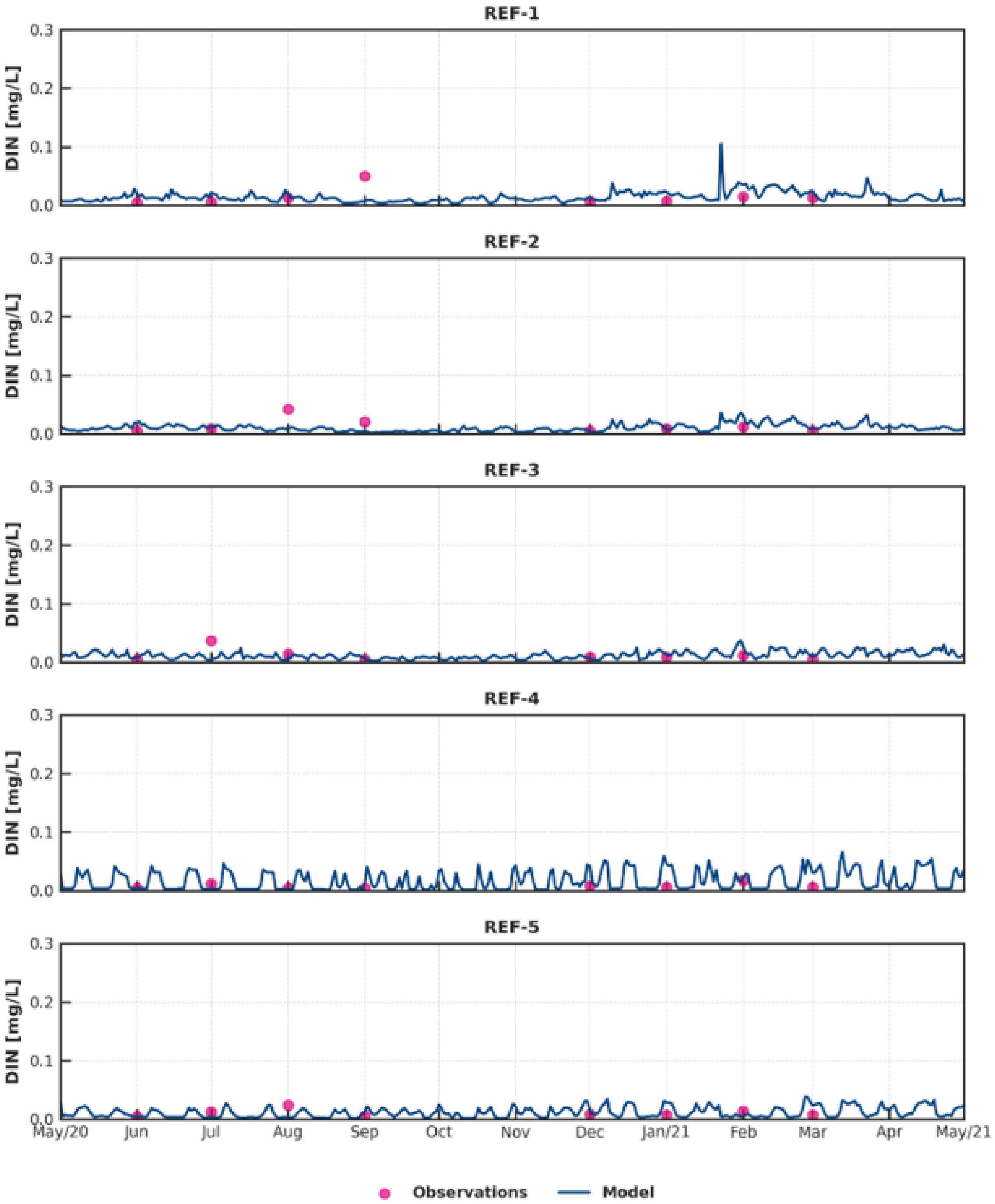


Figure A4: Time series of near surface model and observed data for DIN concentrations in mg/L at REF locations for the model period.

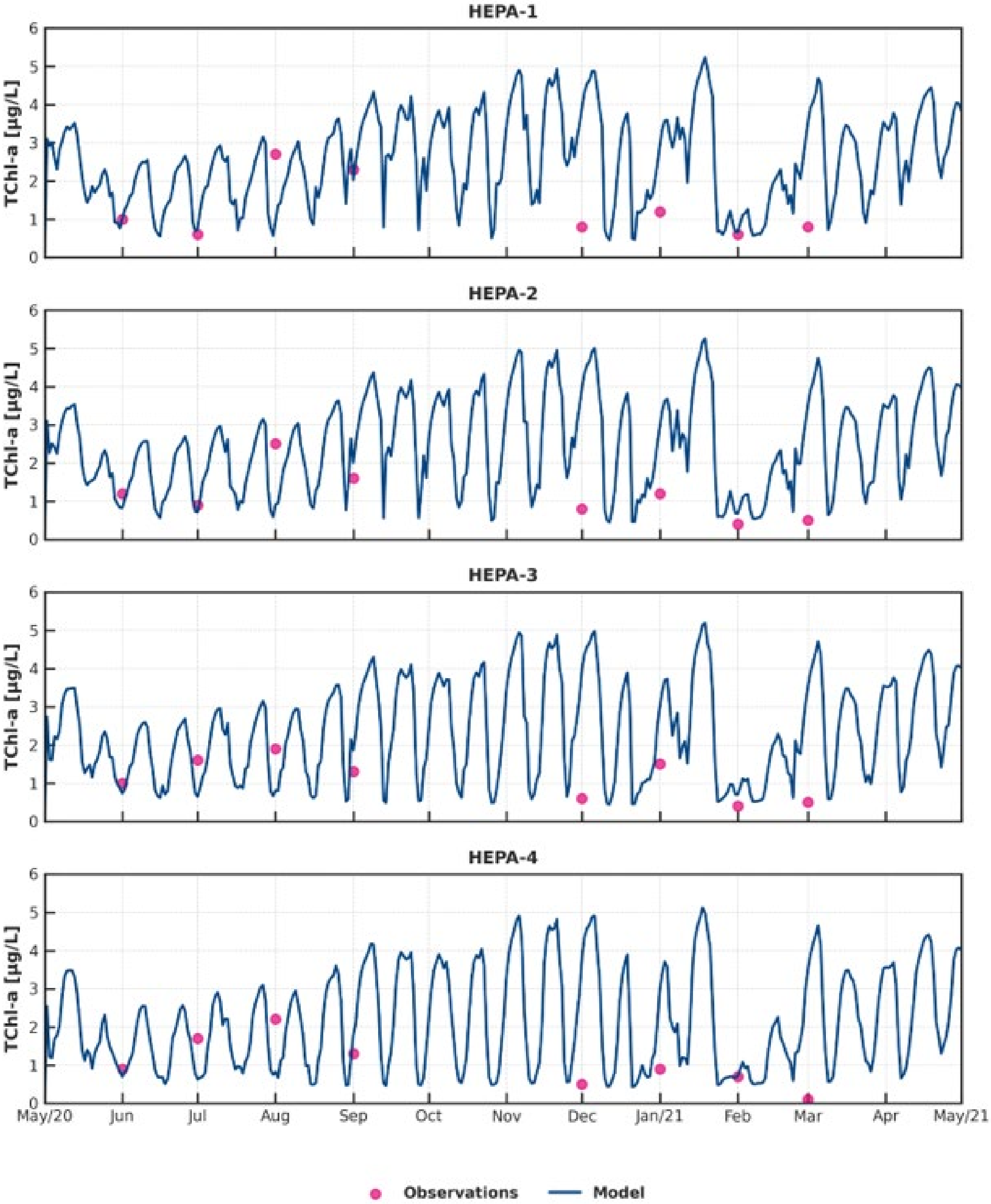


Figure A5: Time series of near surface model and observed data for TChl-a concentrations in µg/L at HEPA locations for the model period.

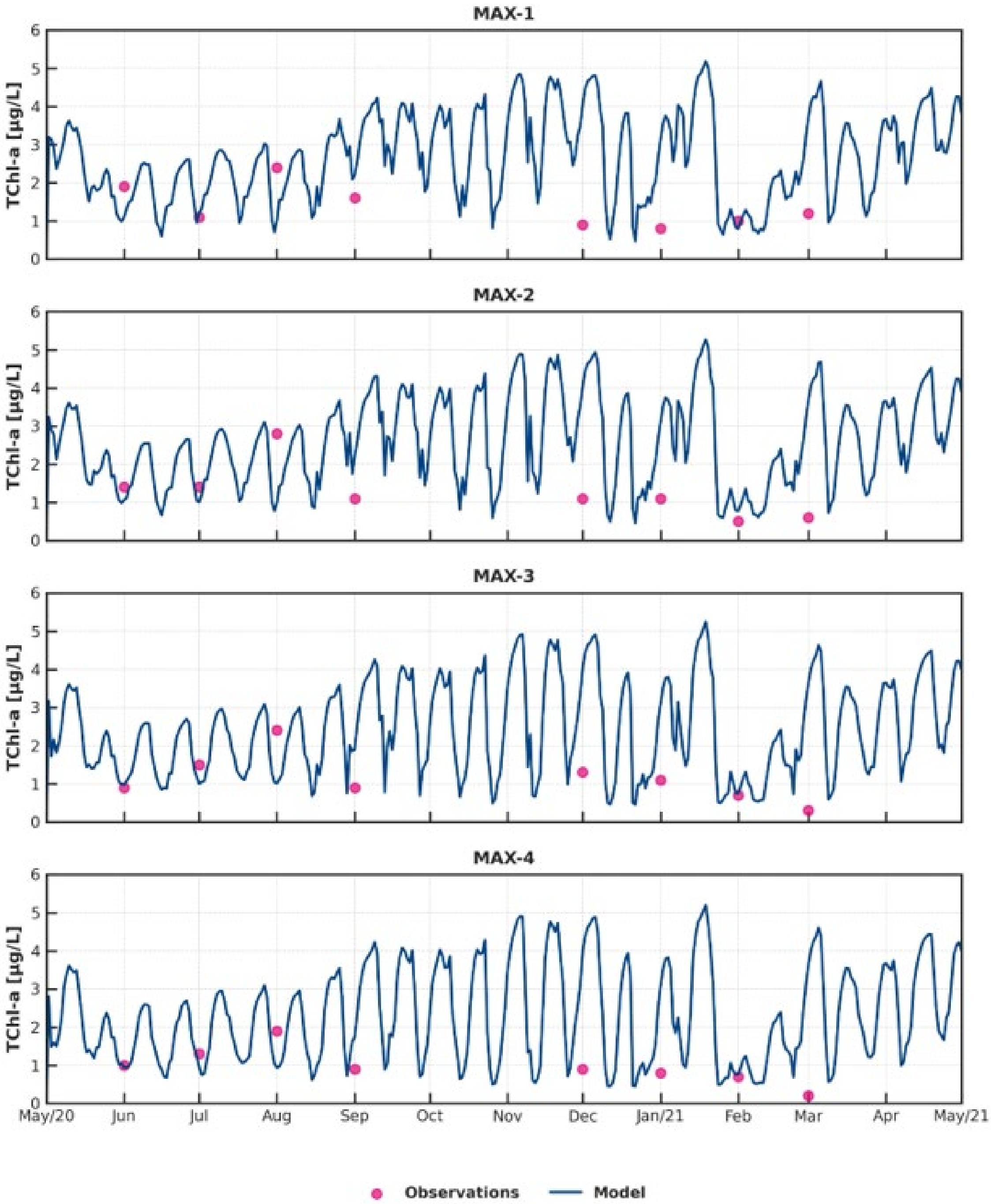


Figure A6: Time series of near surface model and observed data for TChl-a concentrations in µg/L at Max-EPA locations for the model period.

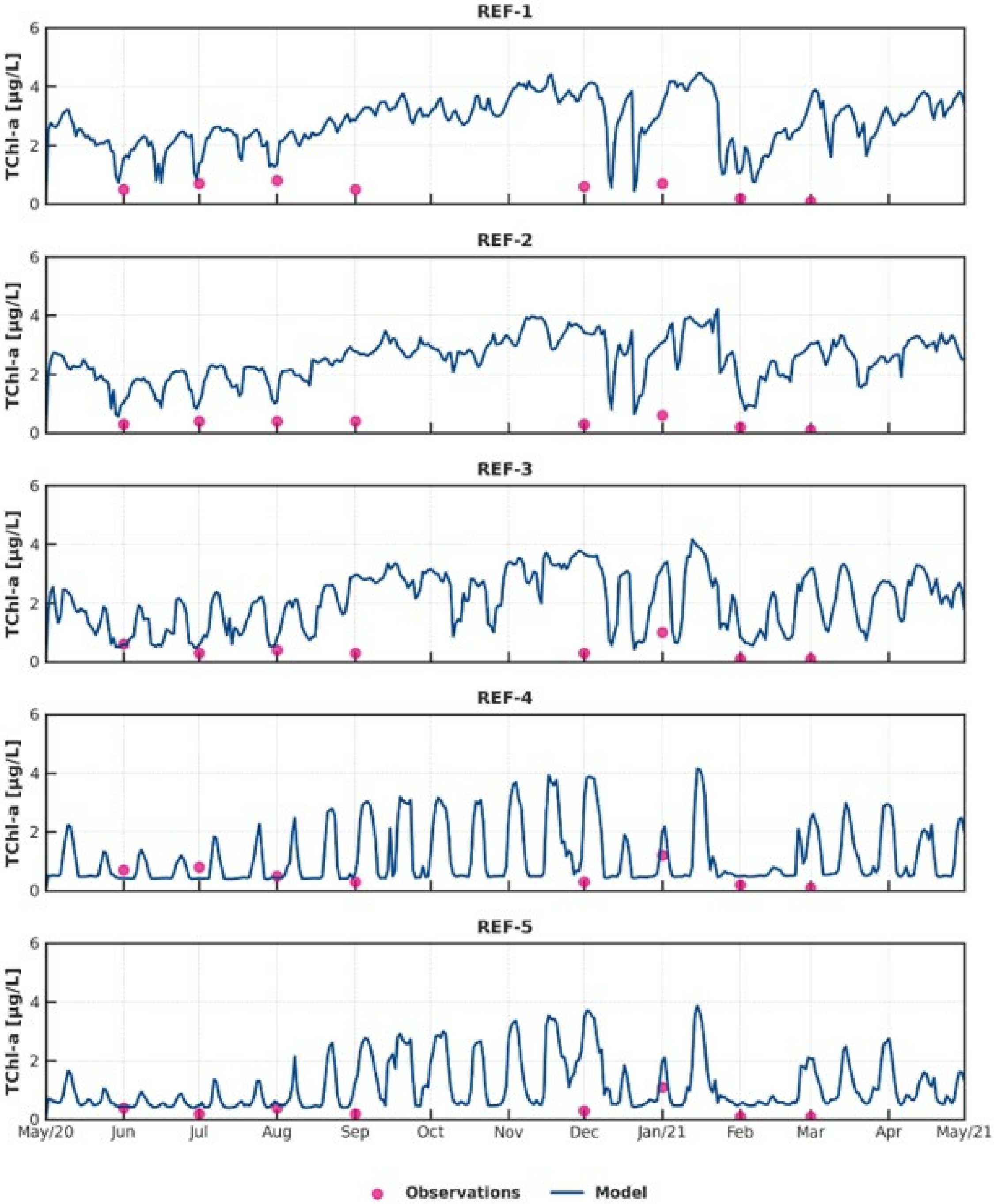


Figure A7: Time series of near surface model and observed data for TChl-a concentrations in µg/L at REF locations for the model period.

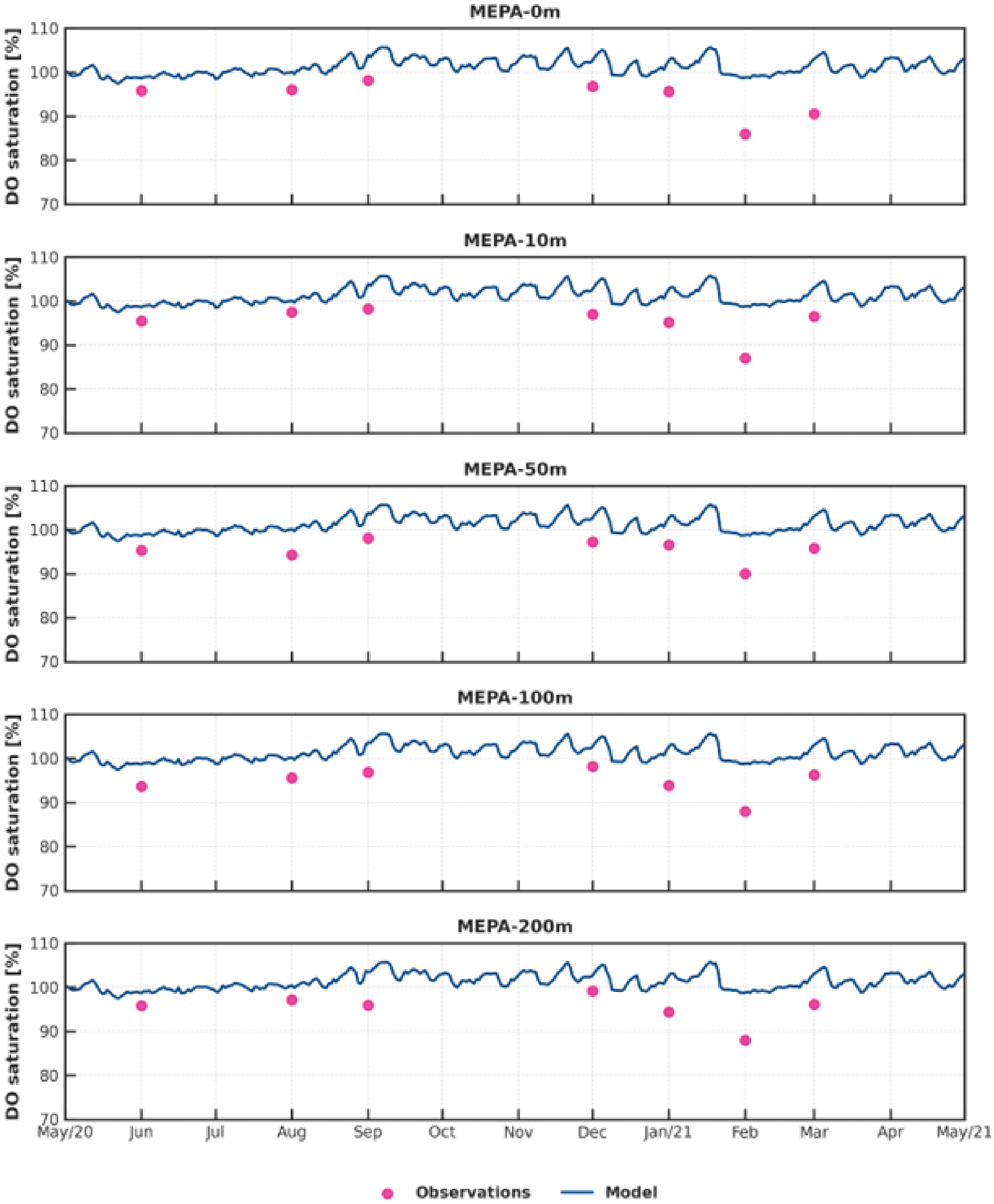


Figure A8: Time series of near seabed model and observed data for DO Saturation (%) at MEPA locations for the model period.

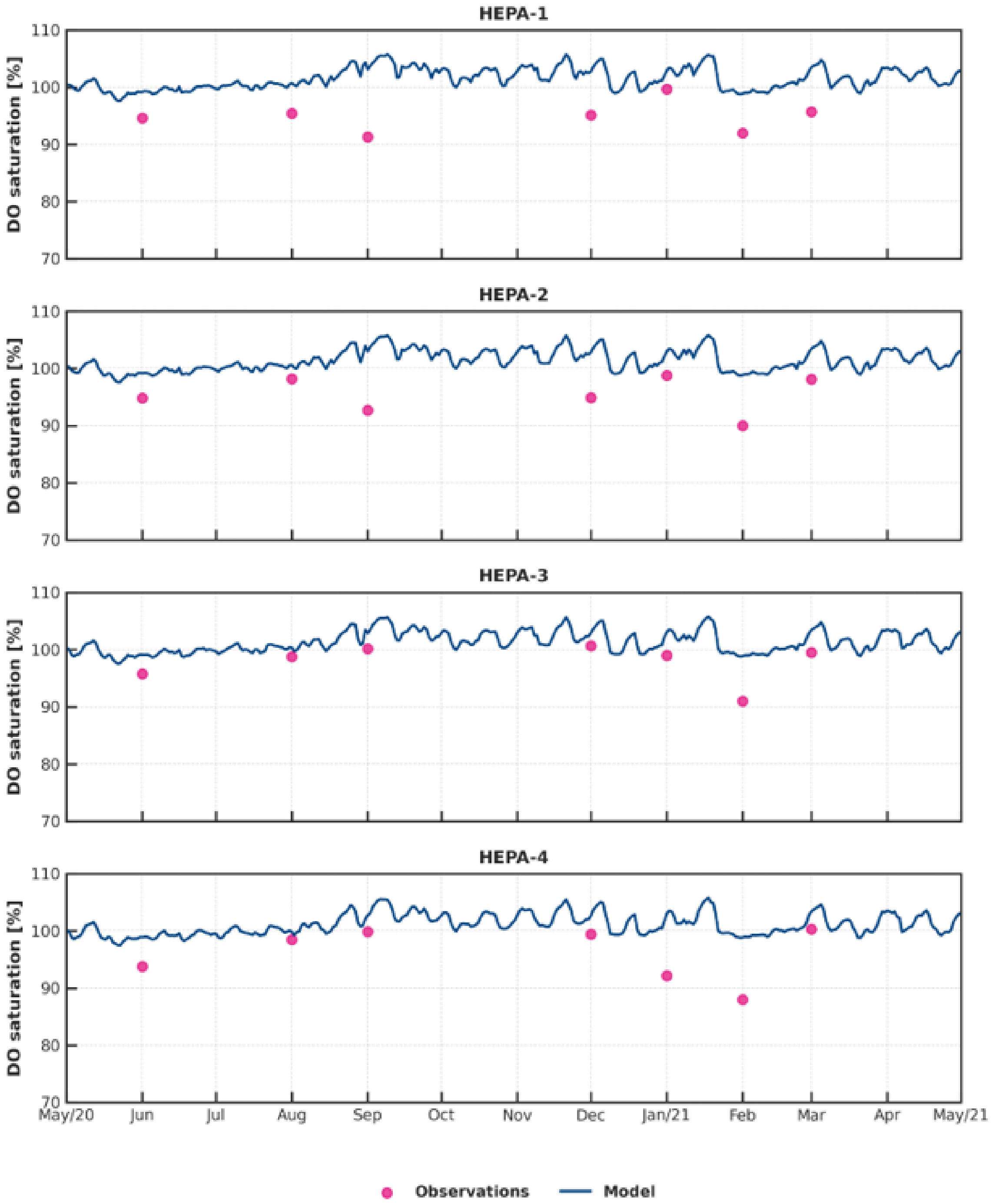


Figure A9: Time series of near seabed model and observed data for DO Saturation (%) at HEPA locations for the model period.

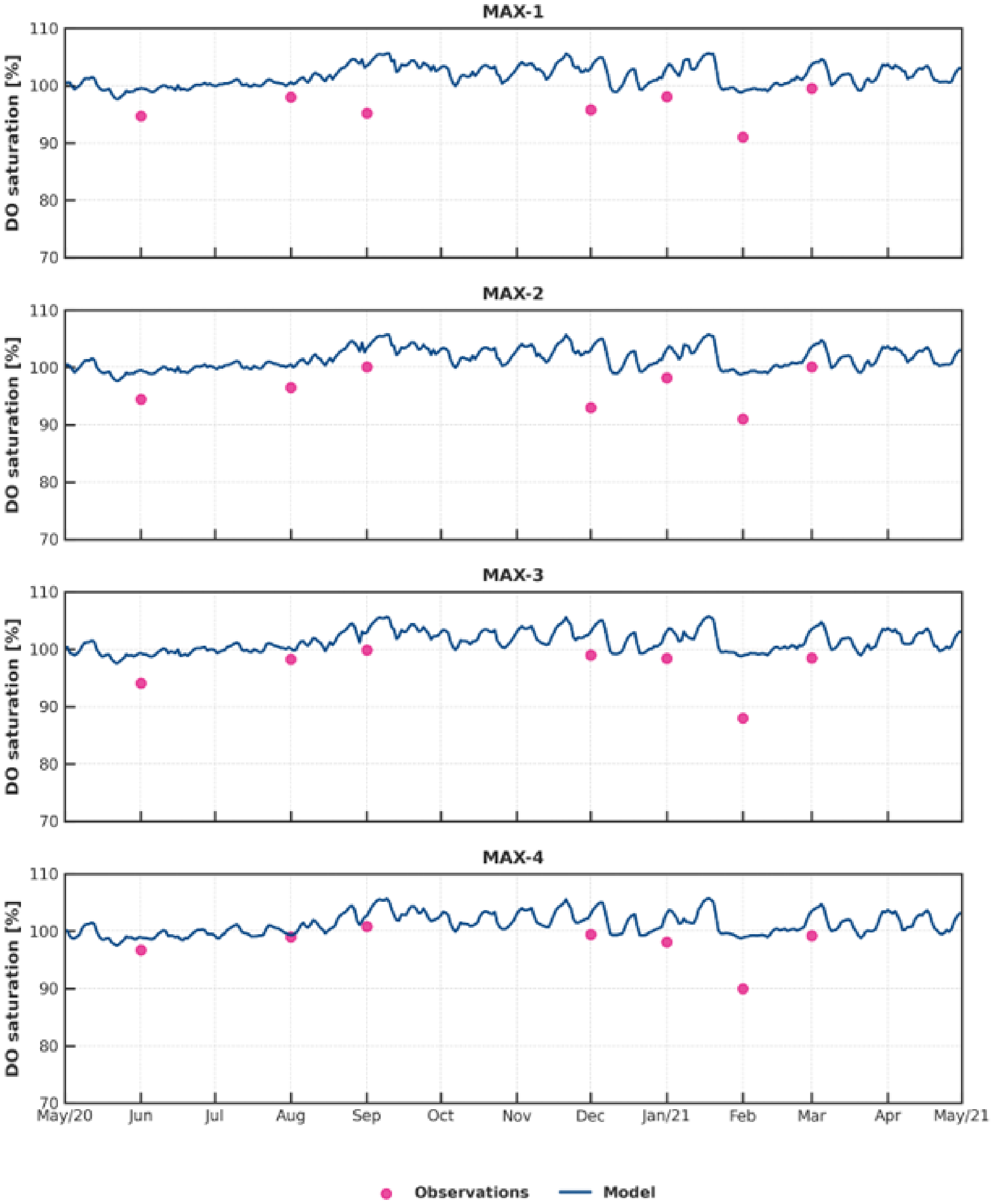


Figure A10: Time series of near seabed model and observed data for DO Saturation (%) at MaxEPA locations for the model period.

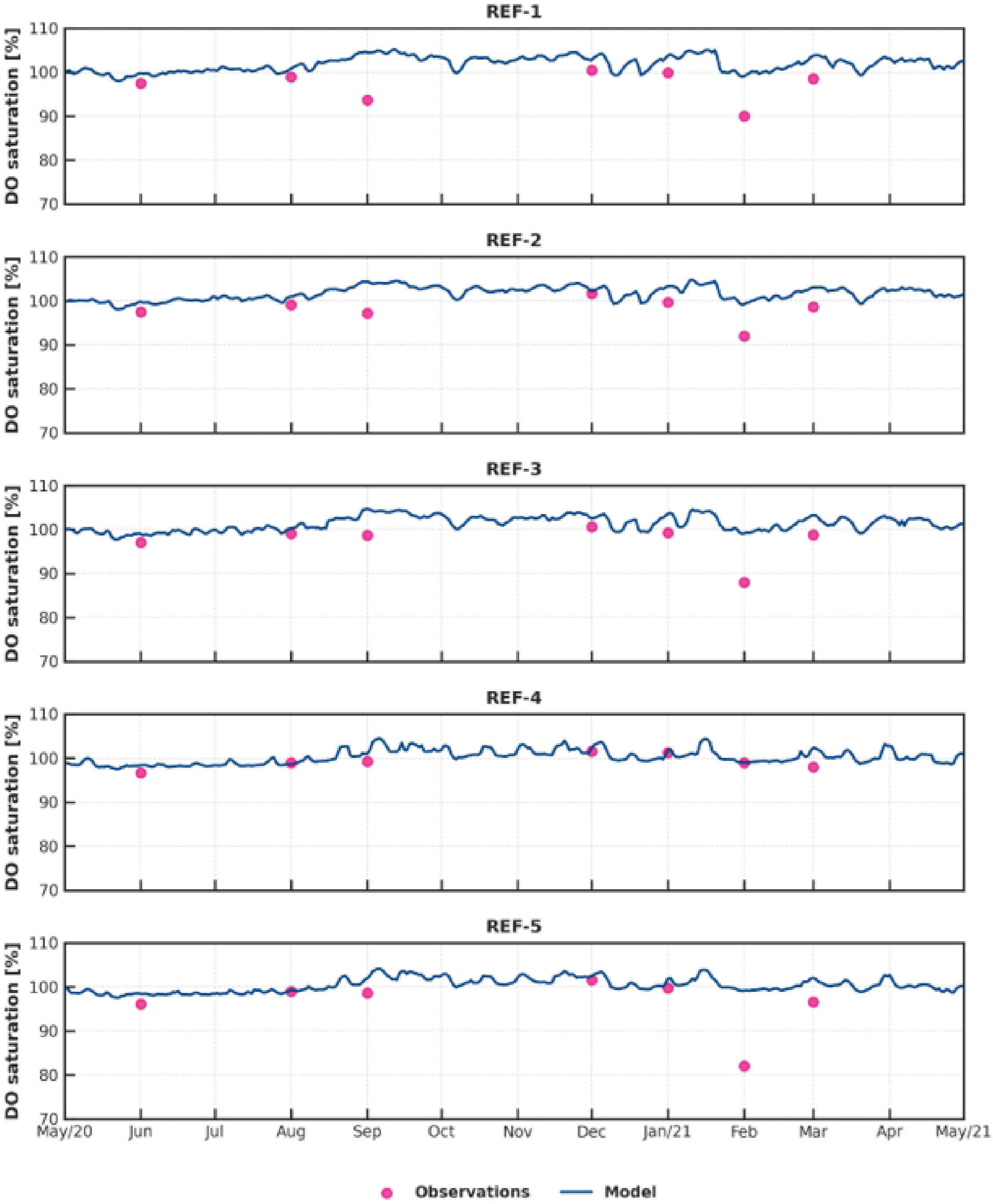
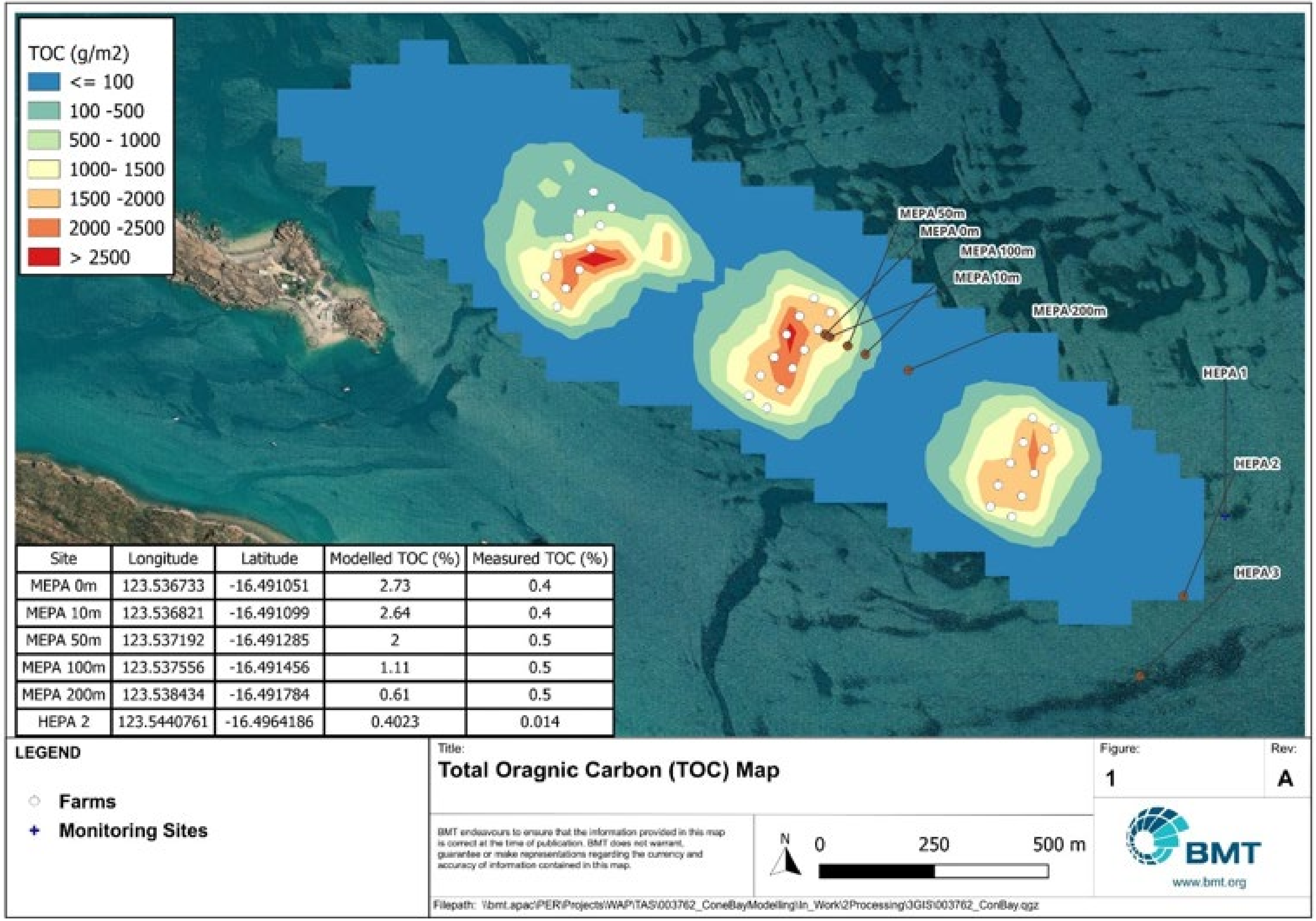


Figure A11: Time series of near seabed model and observed data for DO Saturation (%) at REF locations for the model period.



Site	Longitude	Latitude	Modelled TOC (%)	Measured TOC (%)
MEPA 0m	123.536733	-16.491051	2.73	0.4
MEPA 10m	123.536821	-16.491099	2.64	0.4
MEPA 50m	123.537192	-16.491285	2	0.5
MEPA 100m	123.537556	-16.491456	1.11	0.5
MEPA 200m	123.538434	-16.491784	0.61	0.5
HEPA 2	123.5440761	-16.4964186	0.4023	0.014

Figure A12: Average monthly modelled TOC footprint (g/m²) including a table comparing modelled and measured TOC percentages.

Appendix B Supplementary Plots (Average Values)

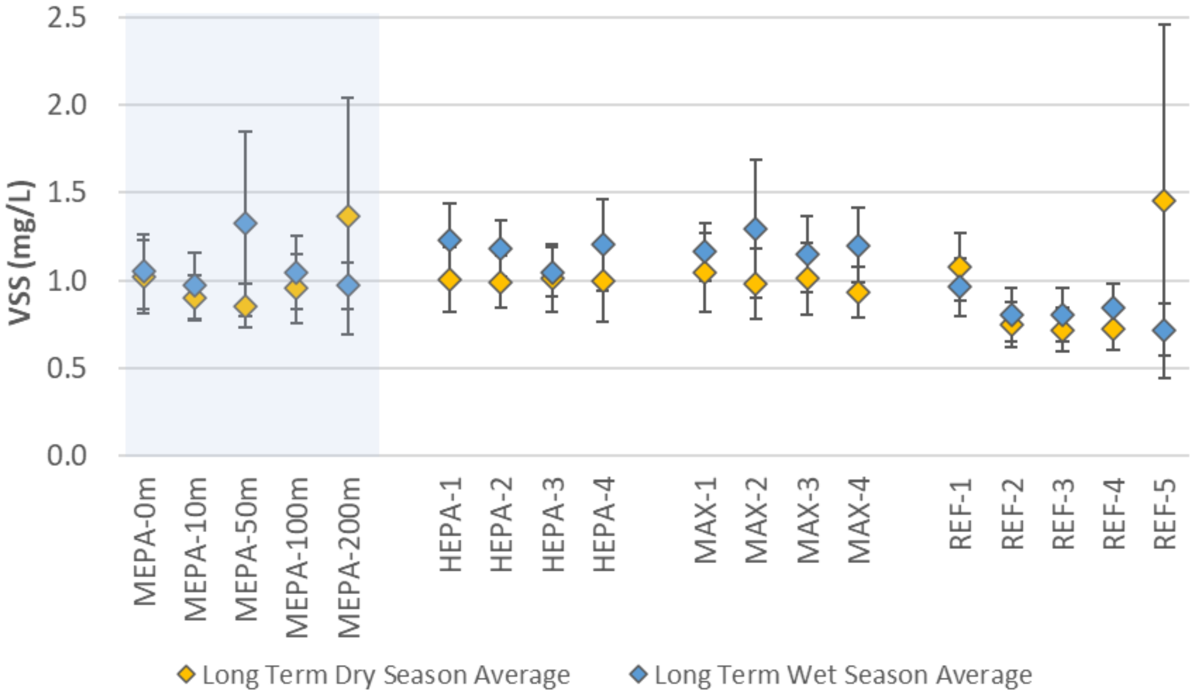


Figure B1: Average (±95% CI) surface VSS concentrations for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

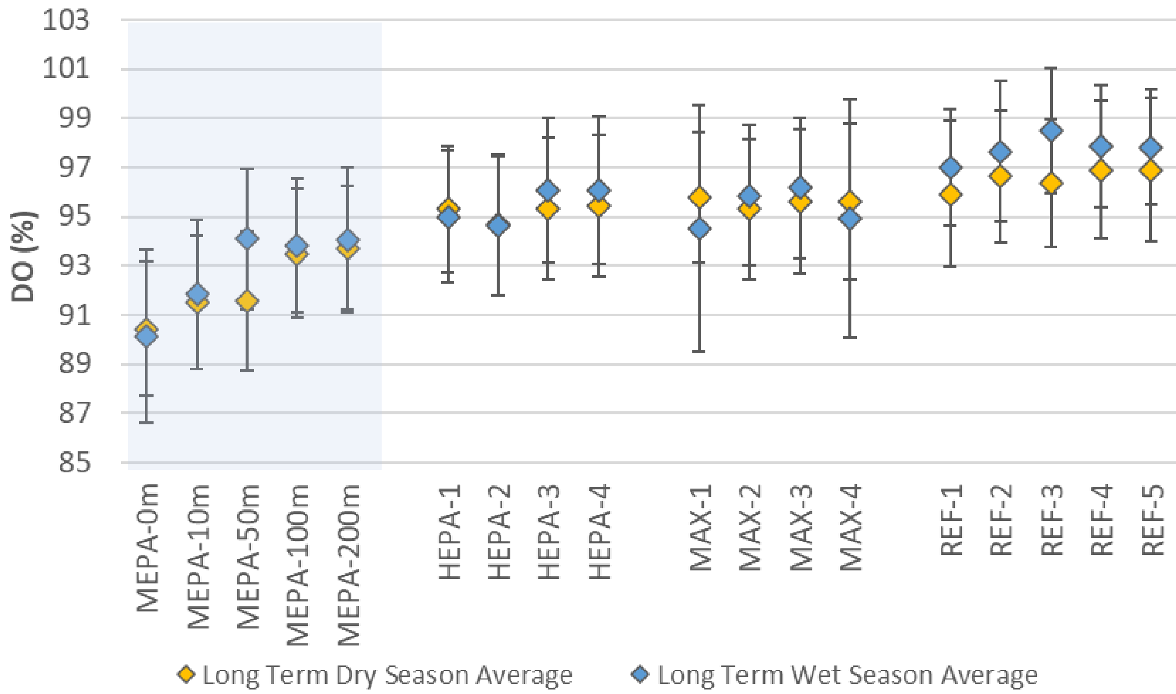


Figure B2: Average (±95% CI) bottom DO % saturation values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

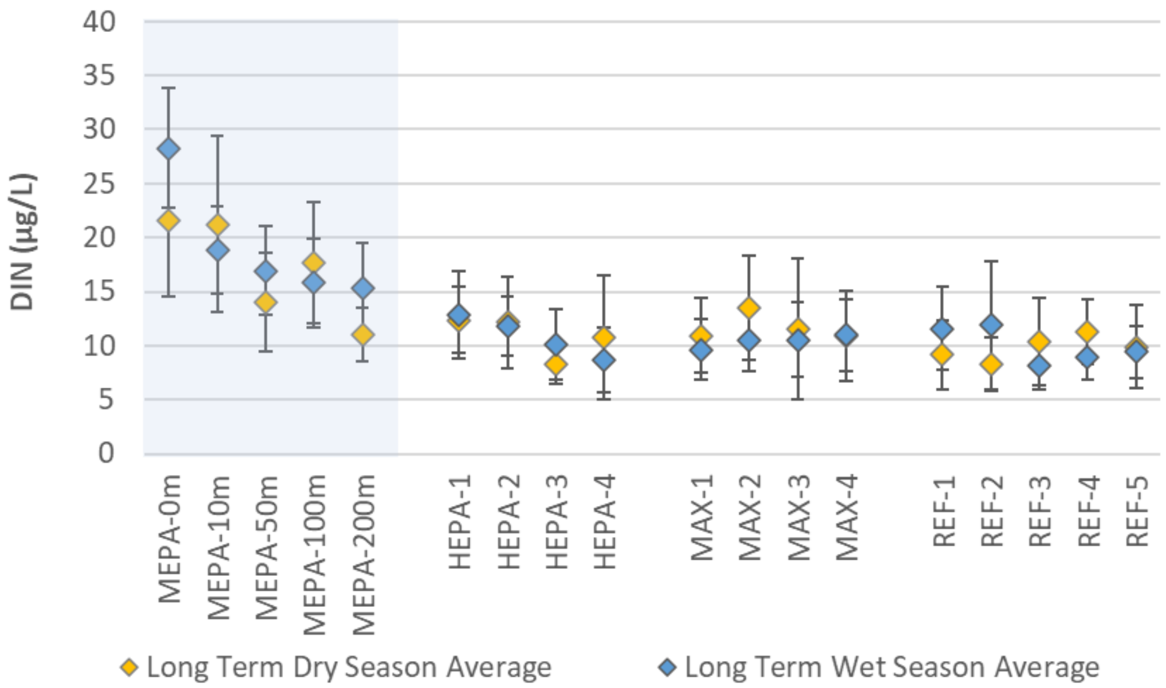


Figure B3: Average (±95% CI) surface DIN concentrations for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

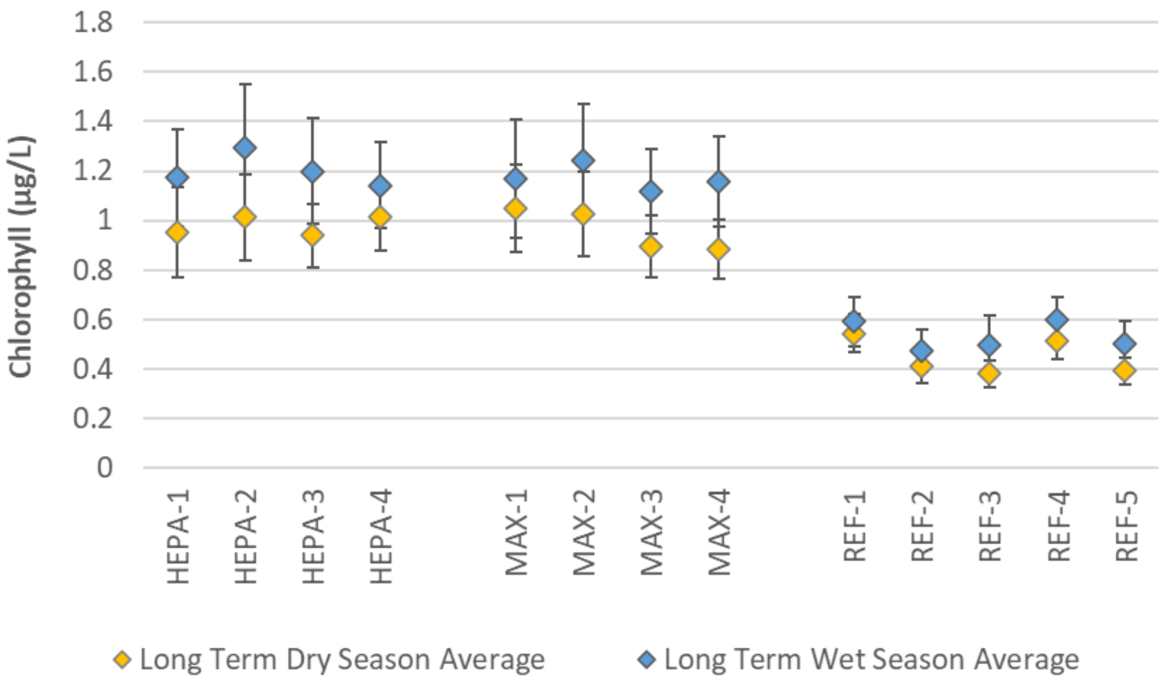


Figure B4: Average (±95% CI) surface chlorophyll-a concentrations for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

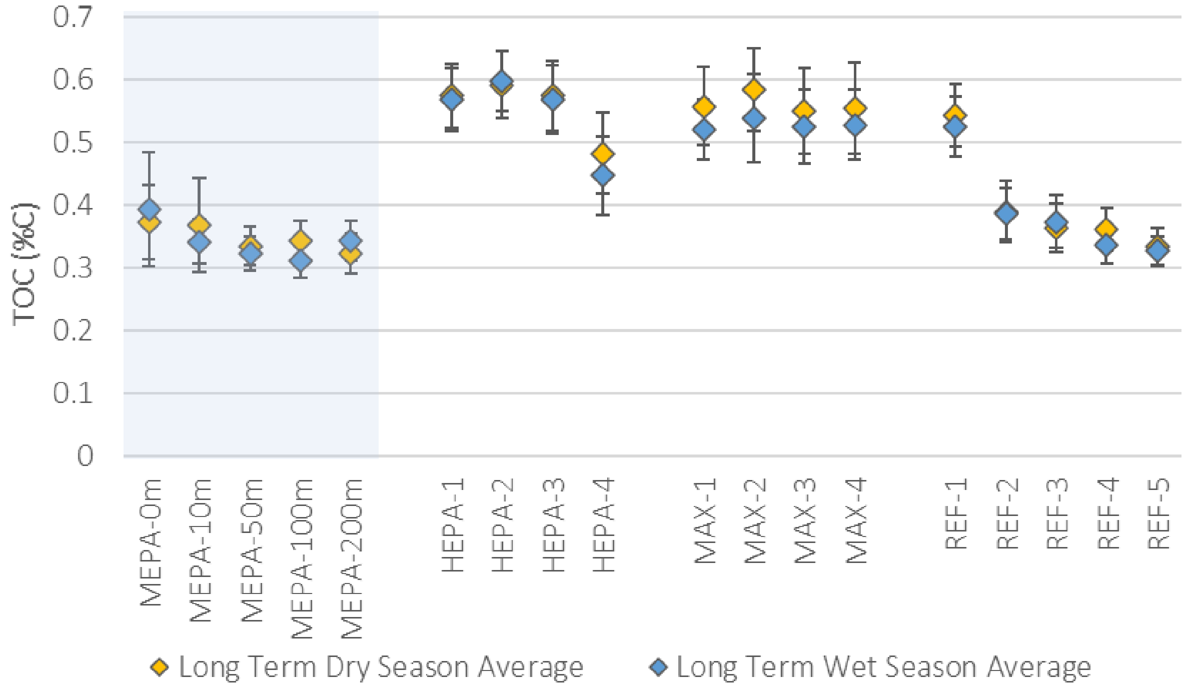


Figure B5: Average (±95% CI) sediment TOC values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

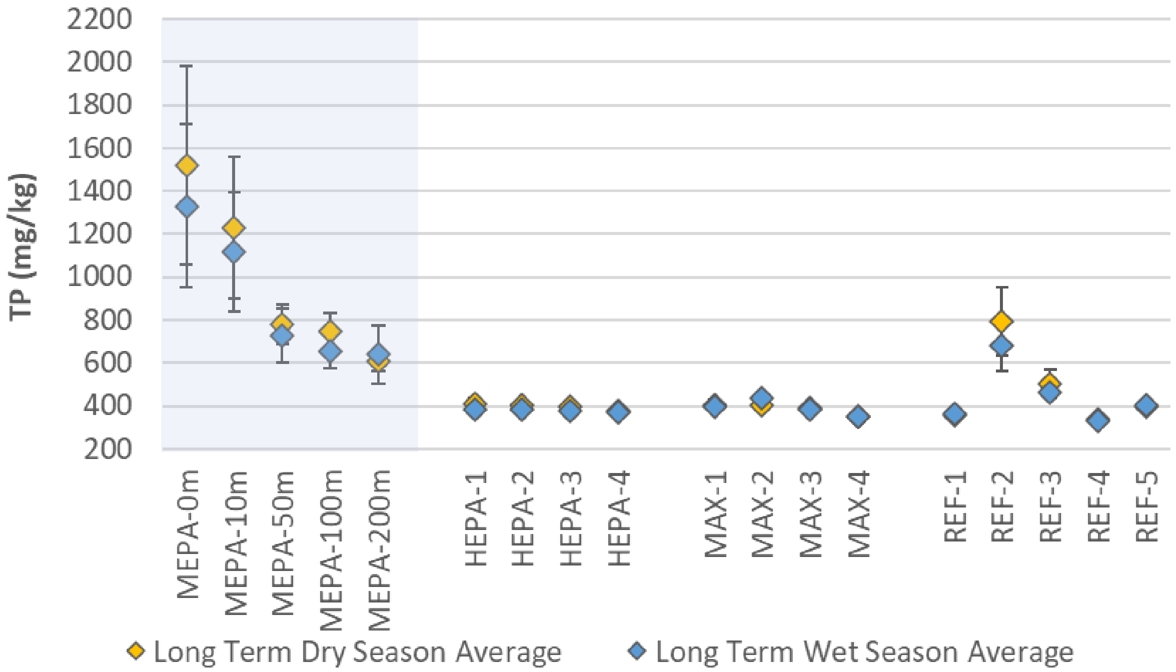


Figure B6: Average (±95% CI) sediment TP values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

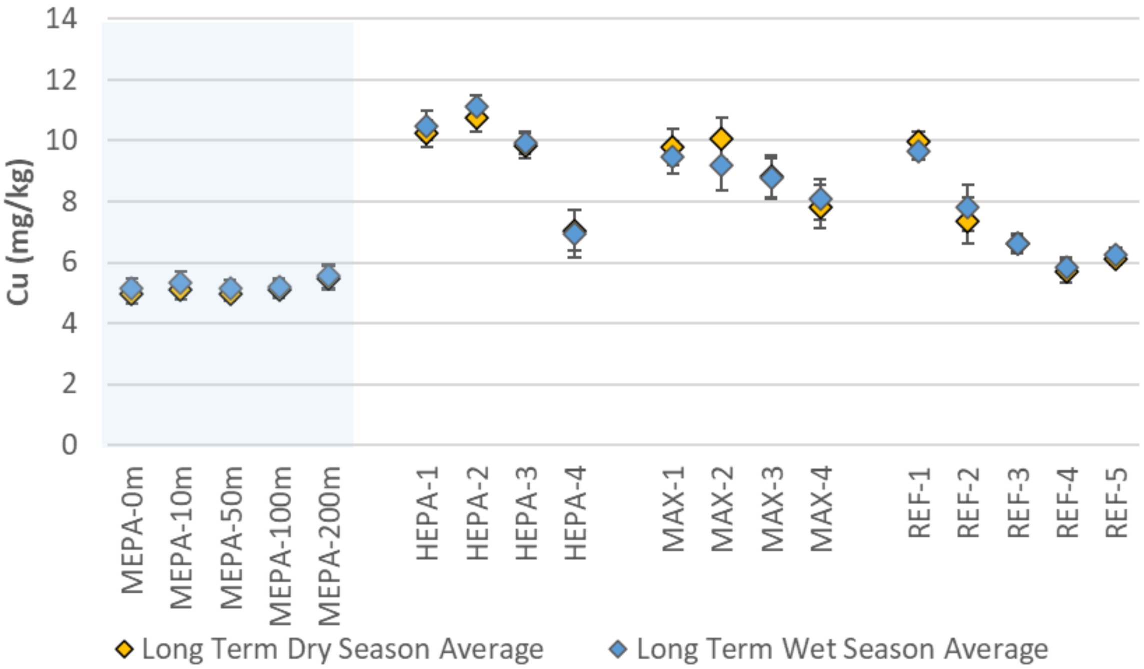


Figure B7: Average (±95% CI) sediment Cu values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

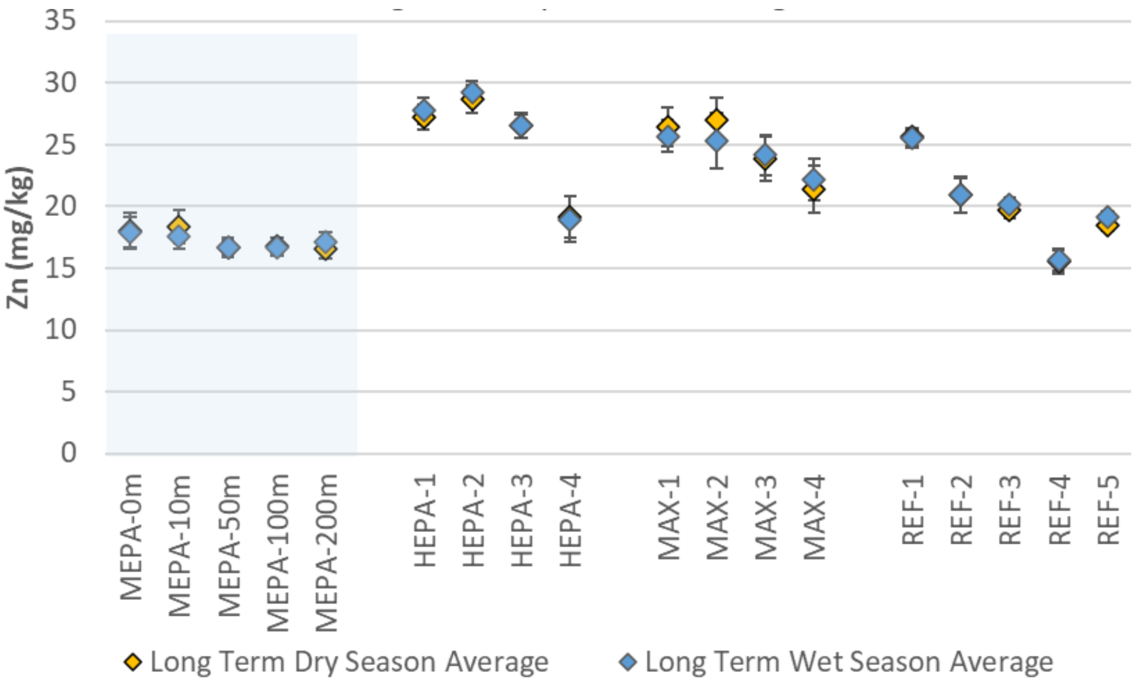


Figure B8: Average (±95% CI) sediment Zn values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

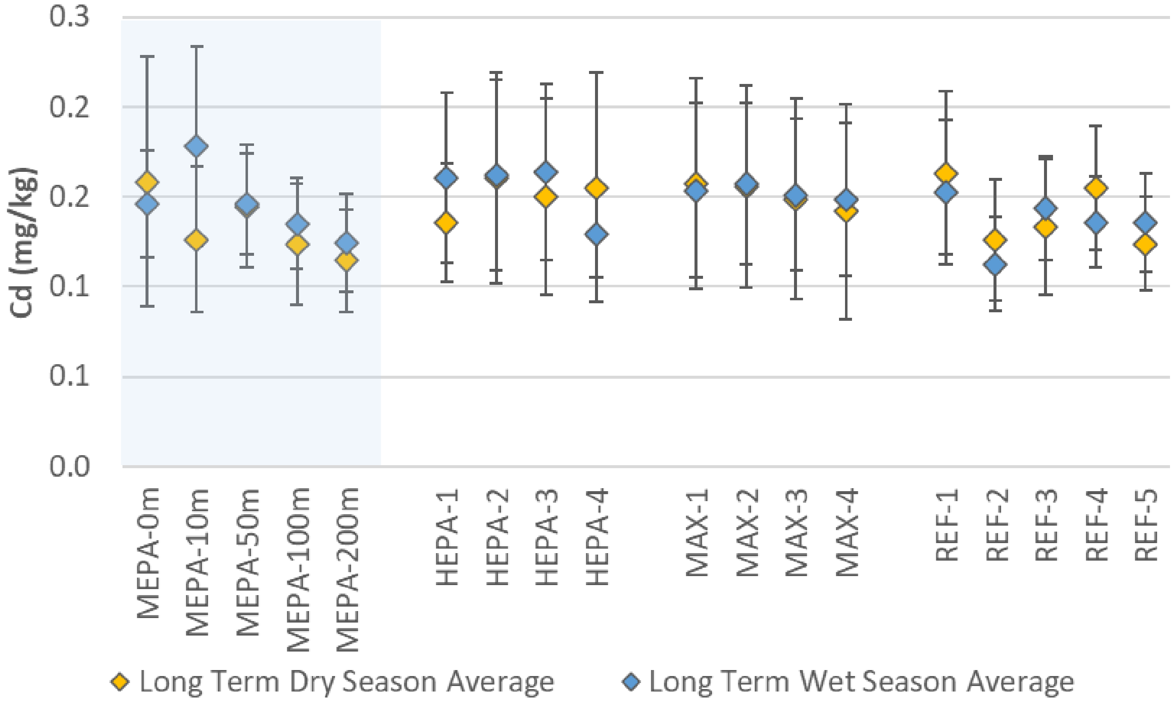


Figure B9: Average (±95% CI) sediment Cd values for the sites within the MEPA, HEPA, MaxEPA and Reference Zones between 2014 and 2025.

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