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Development of standards for assessing water quality in marine coastal waters of Bahrain

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ABSTRACT

Marine coastal waters of Bahrain are under pressure due to human activities and climate change. We used marine monitoring data (2005–2020) from 27 sites to establish baseline conditions and develop standards for assessments of water quality. Five hydrodynamic regions were identified: Oyster Beds, North, West, East, East (Coastal). Data from Oyster Beds sites, likely to be less impacted by human activities, were used to determine baseline conditions. For most parameters, candidate thresholds were based on 50 % and 100 % variation from baseline and 95th percentiles. Comparisons of data against different thresholds showed different outcomes. Overall, results indicate good water quality, with potential concerns in East (Coastal). Trend analyses showed some significant trends in all regions: downward (favourable) for some parameters (e.g. turbidity: North) and upward for others (e.g. nitrate: Oyster Beds, East and East (Coastal)). Future work requires greater understanding around optimum guidelines that protect and mitigate any adverse ecological impacts.

1. Introduction

Much of the Middle East has seen rapid change over the past few decades, with high rates of urbanisation, coastal development and population growth impacting on multiple issues around water quality, plastic pollution, biodiversity and climate change effects (Sheppard, 2016; Wabnitz et al., 2018; Devlin et al., 2019b; Lyons et al., 2020). Many of these changes have been particularly relevant for the countries adjacent to the Arabian Gulf (Fig. 1, referred to hereafter as the Gulf). Maintaining good marine environmental quality in the Gulf is recognised as being crucial for several socio-economic reasons, as seafood represents one of the most important local sources of protein and waters of the Gulf are the main source of drinking water (Al-Majed et al., 2000; ECD, 2009). The Kingdom of Bahrain is located in the Gulf and is facing several of the regional issues and environmental challenges associated with rapid urbanisation, economic development and population growth (DEAP, 2009; Sheppard et al., 2010; Naser, 2015). The majority of the urban and industrial expansion in recent years has occurred along its coastal margins, with most of the population (85 %) living in close proximity to the sea (Information and eGovernment Authority, 2018). This, along with the extensive land reclamation activity, associated industrial and domestic effluent discharges of chemical pollutants and sewage discharges, has resulted in the degradation of the Bahrain coastal ecosystems (DEAP, 2009; Burt et al., 2013; Naser, 2015).

The Gulf is a relatively shallow, semi-enclosed hypersaline sea with high evaporation rates and low flushing rates (Sheppard, 1993; Sheppard et al., 2010). Pollutants discharged from land into marine waters may gradually accumulate due to more limited dilution and slower dispersion rates than in open well-flushed marine systems (Alosairi and Pokavanich, 2017). Differences in hydrology and flushing create variable characteristics across Gulf waters, and the coastal waters around Bahrain are influenced by these hydrological differences. Seawater along the west coast of Bahrain has a higher salinity (averaging 52.59) than the east coast (averaging 43.6); seawater on the north coast is characterized by intermediate salinities, with an average of 46.59 reported in earlier reports (ECD, 2009). These differences are partly due to the geographic position of Bahrain with only a shallow, relatively narrow stretch of water separating the west coast from the Arabian

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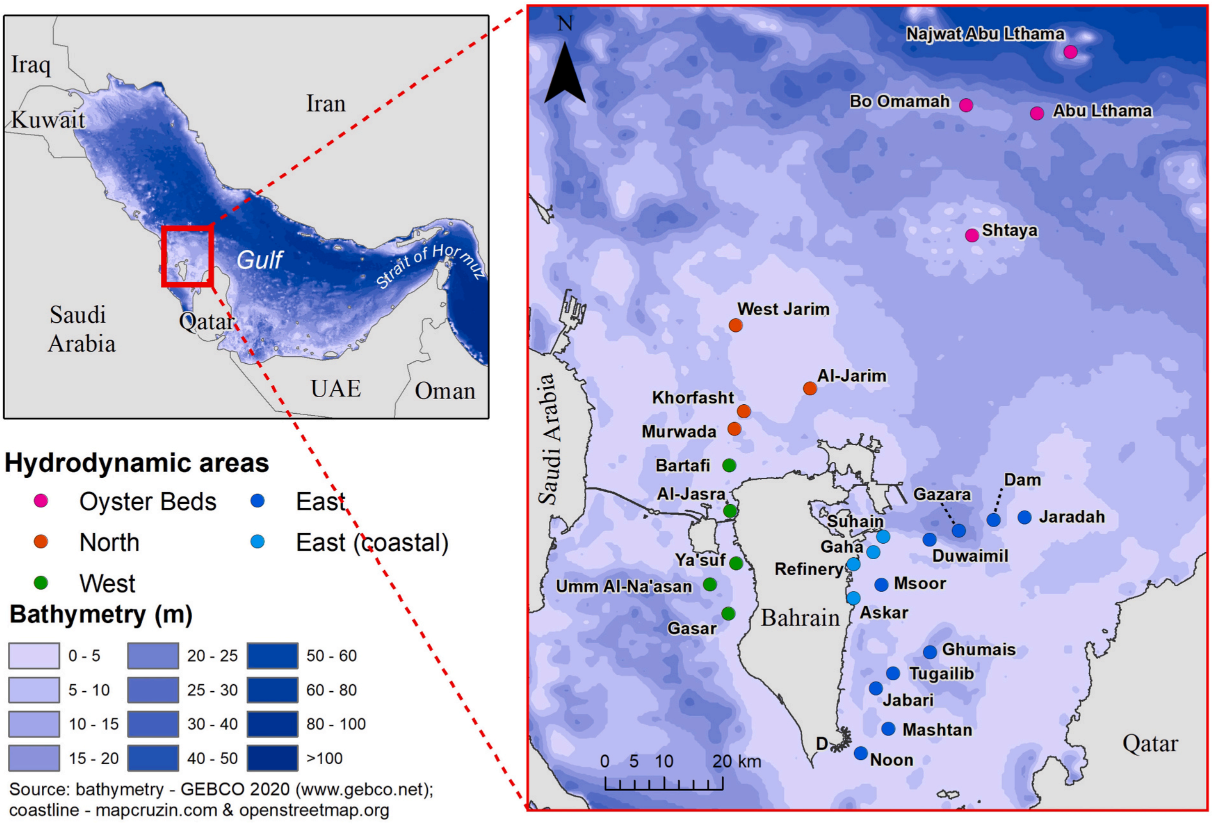
mainland and associated hydrodynamic conditions.

The Gulf is connected to the Indian Ocean through the Strait of Hormuz and the Gulf of Oman and relies on currents in the Strait for exchanges of sea water and nutrients with the Indian Ocean. Due to the sub-tropical location of the region, surface concentrations of nutrients and chlorophyll (Chl) would be expected to be low (e.g. <1 μM nitrate, <0.1 μM phosphate and <1 μg Chl l^{-1}) and consistent with concentrations in oligotrophic waters. Data from the World Ocean Atlas (2013) indicate that Oman's coastal waters in the Arabian Sea show higher nutrient concentrations during the local spring/summer upwelling season, but there is little evidence that this water is advected into the Gulf via the Strait of Hormuz. Bahrain's marine environment also receives anthropogenic inputs of nutrients due to activities such as sewage discharges, which are a common issue across the Gulf (Morel et al., 2010; Quigg et al., 2013; Trade Arabia, 2015; Sheppard, 2016; Devlin et al., 2019b).

Sewage discharges and other inputs of nutrients to the marine environment are a global concern with multiple reports of negative impacts on the adjacent ecosystems (Sheppard, 1993; Glibert et al., 2002; Taebi et al., 2005; Diaz and Rosenberg, 2008; Van Lavieren et al., 2011; Quigg et al., 2013; Garmendia et al., 2015). These impacts include excessive algal growth, oxygen deficiency and mortality of benthic fauna and fish (Tett et al., 2007; Devlin et al., 2011). Rapid population growth in Bahrain and across the region has placed severe pressure on the existing wastewater management infrastructure and sewage pollution is widely reported across the Gulf (Lyons et al., 2015; Saeed et al., 2015; Trade Arabia, 2015; Le Quesne et al., 2018). Recent studies demonstrate a clear link between inputs of nutrients via wastewater discharge, deteriorating water quality conditions (Naser, 2013; Al-Sarawi et al., 2015; Smith et al., 2015; Saeed et al., 2017; Devlin et al., 2019b) and ecosystem impacts such as harmful algal blooms (Richlen et al., 2010), fish kills (Glibert et al., 2002), and damage to coral reefs (Sheppard et al., 2010; Sheppard et al., 2012; Sheppard, 2016), benthic organisms (Al-Farraj et al., 2012) and biodiversity (Sale et al., 2011; Naser, 2014). Other studies focus on other pollutants (such as chemical contaminants, including metals, pesticides, polycyclic aromatic hydrocarbons), using predominantly sediment samples, to determine risks and/or impacts of discharges on sediment quality and marine habitats of ecologically and economically important species such as dugongs and green turtles (Naser, 2013; Bersuder et al., 2020; Nicolaus et al., 2022).

Marine monitoring has been carried out intermittently in Bahrain since the 1980s. More routine monitoring has been conducted by the Supreme Council for the Environment (SCE) since 2005 or 2007 at 23 sites in coastal waters (within 20 km of the coast; Fig. 1, Table 1; EPA, 1995). Since 2014, four sites in the north Oyster Beds region in the central Gulf have also been monitored (Fig. 1). Abdulla (2019) proposed that the north Oyster Beds sites were likely to be less impacted by human activities and could be used to set background (baseline) conditions for assessments of water quality in the nearshore region.

The use of water quality monitoring data in assessments of environmental status (e.g. DEAP, 2009) requires the development of standards or guidelines for key water quality parameters. Water quality guidelines have been developed in a number of regions, e.g. in Europe, the USA, Australia and the Middle East (EIMP, 2001a; EIMP, 2001b; Ministry of the Environment, 2002; UNEP/MAP, 2005; Department of Environment and Science, 2009; Brodie et al., 2011; Devlin et al., 2011; Kress et al., 2019). Assessment of data against water quality guidelines, often as thresholds, provides a useful approach for assessments of status (Al-Majed et al., 2000; Foden et al., 2011; HELCOM, 2015; Poikane et al., 2019). Much of the guidance on the setting of quality guidelines or thresholds is based on establishing background concentrations specific to the region being assessed using historical data or model data of historical conditions. These may be considered to represent near-pristine conditions, even though it is difficult to identify the characteristics of



Source: bathymetry - GEBCO 2020 (www.gebco.net); coastline - mapcruzin.com & openstreetmap.org

Fig. 1. Map of Monitoring sites for Bahrain Supreme Council for the Environment (SCE) Sediment and Water Quality Monitoring Programs. Sites are colour-coded to indicate hydrodynamic areas.

Table 1

Description of the hydrodynamic regions identified for data analysis. Depths (*) were estimated from bathymetry. Available data from 2005 to 2020 were analysed. Oyster Beds sites were monitored from May 2014. n = number of months sampled.

Region	Sites	Description	Depth range* (m)	Monitoring data	*n*
Oyster Beds	• Abu Lthama • Bo Omamah • Najwat Abu Lthama • Shtaya	Outermost sites (4) in the Gulf which are less affected by anthropogenic activities and likely to be representative of pristine conditions. All sites are more than 20 km from the coast of Bahrain.	5-16	• May 2014-Nov 2020 • May 2014-Nov 2016 • May 2014-Nov 2016 • May 2014-Nov 2020	• 27 • 11 • 11 • 27
North	• Al-Jarim • Khorfasht • Murwada • West Jarim	Sites (4) on the north coast of Bahrain with salinities at intermediate values between the Gulf and other sites. Sites located 8 to 15 km from the coast.	1.8-5.3	• Mar 2005-Nov 2020 • Apr 2007-Oct 2016 • Apr 2007-Nov 2020 • May 2014-Nov 2016	• 63 • 39 • 55 • 11
West	• Al-Jasra • Bartafi • Gasar • Umm Al-Na'asan • Ya'suf	Sites (5) on the west coast of Bahrain which are characterized by the highest salinity conditions. All sites are within 6 km of the coast.	0.1-16	• Mar 2005-Nov 2020 • Apr 2007-Nov 2016 • Apr 2007-Nov 2016 • Apr 2007-Nov 2020 • Apr 2007-Nov 2020	• 63 • 39 • 38 • 55 • 55
East	• Askar • Dam • Duwaimil • Gaha • Gazara • Ghumais • Jabari • Jaradah • Mashtan • Msoor • Noon • Refinery • Suhain • Tugailib	Sites (14) on the east coast of Bahrain with lower salinities (<42). Sites within 20 km of the coast.	0.5-20	• Mar 2005-Nov 2020 • Apr 2007-Oct 2016 • Apr 2007-Oct 2016 • Apr 2007-Oct 2016 • Apr 2007-Nov 2020 • Apr 2007-Nov 2020 • Apr 2007-Oct 2016 • Apr 2007-Nov 2020 • Apr 2007-Nov 2020 • Apr 2007-Oct 2016 • Apr 2007-Oct 2016 • Mar 2005-Nov 2020 • Apr 2007-Oct2016 • Apr 2007-Oct 2016	• 63 • 39 • 39 • 39 • 54 • 55 • 39 • 55 • 55 • 39 • 39 • 63 • 39 • 39
East (Coastal)	• Askar • Gaha • Refinery • Suhain	A subset (4) of 'East' sites which were closest to the coast were analysed separately to investigate potential influence of human activity in inshore waters. All East (Coastal) sites are within 4 km of the natural coastline.	0.5-4.7	See Above	

a pristine system (Andersen et al., 2004; Ferreira et al., 2011; OSPAR, 2013). Water quality guidelines generally present data as a statistical measure, such as an annual or seasonal average (Al-Azri et al., 2010; OSPAR, 2013; Pokavanich et al., 2013; Al-Ansari et al., 2015; Devlin et al., 2019a). In the case of chlorophyll, thresholds have been determined based on seasonal averages, with percentiles used to assess monitoring data against these guidelines. Assessments of status may include analyses of long-term trends in the data in order to determine if observed changes are significant and in the direction required (e.g. EU, 2008; COM, 2014; Devlin et al., 2019a). For example, for assessing anthropogenic nutrient enrichment and the impacts thereof (i.e. eutrophication; Tett et al., 2007), the direction required is generally downwards for nutrients and upwards for dissolved oxygen.

For Bahrain, as for most of the Gulf, historical data sets are scarce. This study used a combination of in-situ physico-chemical monitoring data collected since 2005 at 27 sites and international guidelines to develop marine water quality standards. While there were gaps in sampling frequency, the monitoring programme provided an opportune data set to determine background (baseline) conditions, propose quality guidelines for future assessments, and compare available data against candidate thresholds. The development and adoption of water quality standards for water quality in Bahrain would facilitate the production of marine environmental health reports, such as being employed in other countries in the region (ROPME, 2013; Devlin et al., 2019b).

2. Methods

2.1. *Monitoring*

2.1.1. *Study sites*

This study considers data from 27 study sites (Fig. 1) where water quality has been monitored most frequently: 23 in coastal waters (within 20 km of the coast; monitored since 2005/7, Table 1) and four at the north Oyster Beds in the central Gulf (>20 km; Table 1, monitored since 2014). Since 2017, sampling has continued at approximately half of the sites (Table 1).

Data (2014–2020) from the north Oyster Beds sites, which are likely to be less impacted by human activities, were used to determine background conditions and develop threshold levels for assessing water quality status in the other regions.

2.1.2. *Data*

Near surface samples were collected for the analysis of key water quality parameters that were monitored regularly: temperature, salinity, total suspended solids (TSS), turbidity, dissolved oxygen, dissolved inorganic nutrients, and chlorophyll concentrations. Details of methods can be found in technical reports (e.g. UNEP/MAP, 2005). Nutrient analyses were carried out following the 1999 and 2010 revisions of the

Manual of Oceanographic Observations and Pollutant Analyses Methods (MOOPAM)[2] published in 1983 by the Regional Organization for the Protection of Marine Environment (ROPME). Results were reported as dissolved nitrite-N, nitrate-N, ammonia-N, phosphate-P and silicate-Si in μg l^{-1}; they are also given here in μM for comparison with other studies. Laboratory derived limits of detection (LOD), describing the sensitivity of the instrument, were 1.5 μg l^{-1} (0.11 μM) for nitrite, 6 μg l^{-1} (0.43 μM) for nitrate, 4 μg l^{-1} (0.29 μM) for ammonium, 2 μg l^{-1} (0.06 μM) for phosphate, and 7 μg l^{-1} (0.25 μM) for silicate. The sensitivity of the temperature sensor was within 0.1 °C.

2.2. Data analysis

Due to disparate locations of study sites, five hydrodynamic regions were identified for data analysis based on salinities (ECD, 2009), water depths and currents (Pokavanich et al., 2014). These regions were named Oyster Beds, North, West, East and East (Coastal) (see Table 1). The East (Coastal) sites are likely to be more impacted by human activities than sites further offshore on the east coast. These sites were analysed separately from, as well as with, the other sites on the east coast.

Data (2005–2020) were analysed for all sites together, by hydrodynamic region and by site to estimate averages and 95th percentiles over the whole time period (2005–2020), by year, by season and by month. Annual averages were used to analyse trends. Prior to data analysis, outliers (see supplementary material, Table S1) were removed from the data set using the interquartile range rule and the 2nd and 98th percentiles (Horn et al., 2001; Solberg and Lahti, 2005).

Total dissolved inorganic nitrogen (DIN) was calculated by summing nitrite-N, nitrate-N and ammonia-N, and used to calculate molar ratios of DIN to phosphate-P (assumed to represent DIP). Where phosphate values were < LOD, DIN:DIP ratios were not calculated (see Table S2). Oxygen saturation levels were estimated from oxygen concentrations, temperature and salinity (Garcia and Gordon, 1992; Alosairi and Pokavanich, 2017).

For seasonal analyses, each season was represented by three months: Winter (January to March), Spring (April to June), Summer (July to September) and Autumn (October to December).

2.3. Development of assessment levels for water quality

In-situ monitoring data (2014–2020) from the four Oyster Beds sites were used to calculate averages and 95th percentiles over the seven-year time-period, as a proxy for background (baseline) conditions in the region.

Preliminary assessment levels (referred to as candidate thresholds) for nutrients, total suspended solids, turbidity and chlorophyll were calculated based on 50 % and 100 % deviation from background conditions (e.g. COM, 2003; OSPAR, 2005; Devlin et al., 2011; Foden et al., 2011; HELCOM, 2015) and 95th percentiles.

Due to limited data availability within each year, candidate thresholds are based on data from all months sampled (January to December).

The Redfield ratio of N:P (16,1; Downing, 1997) plus 50 % deviation was used to calculate a threshold value (24) for the ratio between DIN and DIP.

For dissolved oxygen, thresholds were derived from the literature due to established links between low oxygen and adverse responses in benthic and fish populations. Oxygen concentrations above 6 mg l^{-1} are considered to cause no problems (Best et al., 2007), while concentrations <3–4 mg l^{-1} are considered to be hypoxic (Best et al., 2007; Diaz and Rosenberg, 2008; Levin et al., 2009; Breitburg et al., 2018). Given these action levels, assessment or threshold values should range from 4 to 6 mg l^{-1} (or 40–60 % saturation) to identify problem areas of deficient or reduced oxygen (Best et al., 2007; Foden et al., 2011; OSPAR, 2013). The lower value of 4 mg l^{-1} was adopted here.

2.4. Trend analyses

Over the full time-series (2005–2020), data were analysed using Mann-Kendall non-parametric tests (Mann, 1945; Kendall, 1975; Barry and Maxwell, 2015) to identify trends in the data. Where p-values were <0.05, it was assumed that there was a significant trend. Trends were analysed using annual and seasonal averages.

3. Results

3.1. Monitoring data

3.1.1. Seasonal and temporal variability in the data

3.1.1.1. Physical parameters and dissolved oxygen. When all data were considered together, salinity, turbidity (Fig. 2) and total suspended solids (Fig. S1) showed high variability and no clear patterns in the data.

A strong seasonal pattern was observed in near surface temperature (Fig. 2), with low temperatures in winter (January and February, minimum 13.32 °C) and highest values in summer (July and August, maximum 35.8 °C), decreasing again in Autumn (December, minimum 19.4 °C). Similarly, a seasonal pattern was observed in concentrations of dissolved oxygen (Fig. 2) and showed an inverse relationship with temperature (Fig. 3). Oxygen concentrations were highest in winter (maximum values >10 mg l^{-1}) with values falling below 4 mg l^{-1} in summer and early autumn (July, August, October; Fig. 2). The same seasonal pattern was observed at each site (data not shown). Oxygen saturation levels were all high (above 80 %, Fig. S1) and followed a similar pattern to oxygen concentrations. Data variability was high particularly in April (spring). Some of the variability in calculated saturation levels may be due to variability in salinity values and/or values being higher than the range for which the equations were derived (salinity 0–42, at temperature 0–40 °C).

3.1.1.2. Nutrients and chlorophyll. When all data were considered together (as in Fig. 2), concentrations of nutrients and chlorophyll (Fig. S2) were also highly variable. Nutrient concentrations were frequently below the limit of detection (LOD) of the analytical instrument: the number of values above the LOD (as a percentage, Table S2) was 23.3 % for phosphate, 27.02 % for nitrite, 64.75 % for ammonia and 66.73 % for nitrate. Silicate was the only nutrient with most (95 %) concentrations above the LOD.

Maximum nutrient concentrations (Fig. S2) were relatively low (<6 μM nitrate, <0.7 μM nitrite, <5.4 μM ammonia, <0.5 μM phosphate) except for silicate (up to 15.5 μM). Monthly averages in nutrient concentrations were low (e.g. <2 μM nitrate, <0.14 μM phosphate, Fig. 4; <0.2 μM nitrite, <0.7 μM ammonia, Fig. S3). Seasonal patterns were observed for nitrate (Fig. 4), nitrite (Fig. S3), DIN and DIN:DIP ratios (Fig. S3), which were low in spring and increased through summer; in some autumn and winter months (Fig. 4, Fig. S3), relatively high average values were observed. No seasonal trends were evident for phosphate (Fig. 4), ammonia (Fig. S3) or silicate (Fig. 4). Some months were significantly under-sampled compared with other months, with data for only a few years and sites, as reflected in the higher standard errors (Fig. 4). For example, fewer samples were obtained for nitrate (and other nutrients contributing to DIN, Fig. 4, Fig. S2) in the months of March (10 samples, from years 2005, 2017 and 2019), June (4 samples, all in 2005), September (21 samples, from 2005, 2006 and 2019) and December (22 samples in years 2005, 2015 and 2017).

Monthly averages for chlorophyll were low (generally 0.5–1 μg Chl l^{-1}, Fig. 4). The data show little evidence of seasonality, also possibly due to uneven sampling. In June, the monthly average was highest (*ca*

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[2] Not available electronically but described in UNEP/MAP, 2005.

1.7 μg l^{-1}, Fig. 4) but the associated error was high; only four samples were collected in this month, in 2005, and values ranged from *ca* 0.3 to 3.7 μg l^{-1} (Fig. S2).

3.1.2. *Hydrodynamic regions (areas)*

3.1.2.1. Physical parameters and dissolved oxygen. Data from this study showed that average monthly salinities were lowest in the Oyster Beds region (Fig. 5; 39.39–40.64, Table 2) and highest in West (50.92–53.27, Table 2). In North, salinity values were variable and intermediate

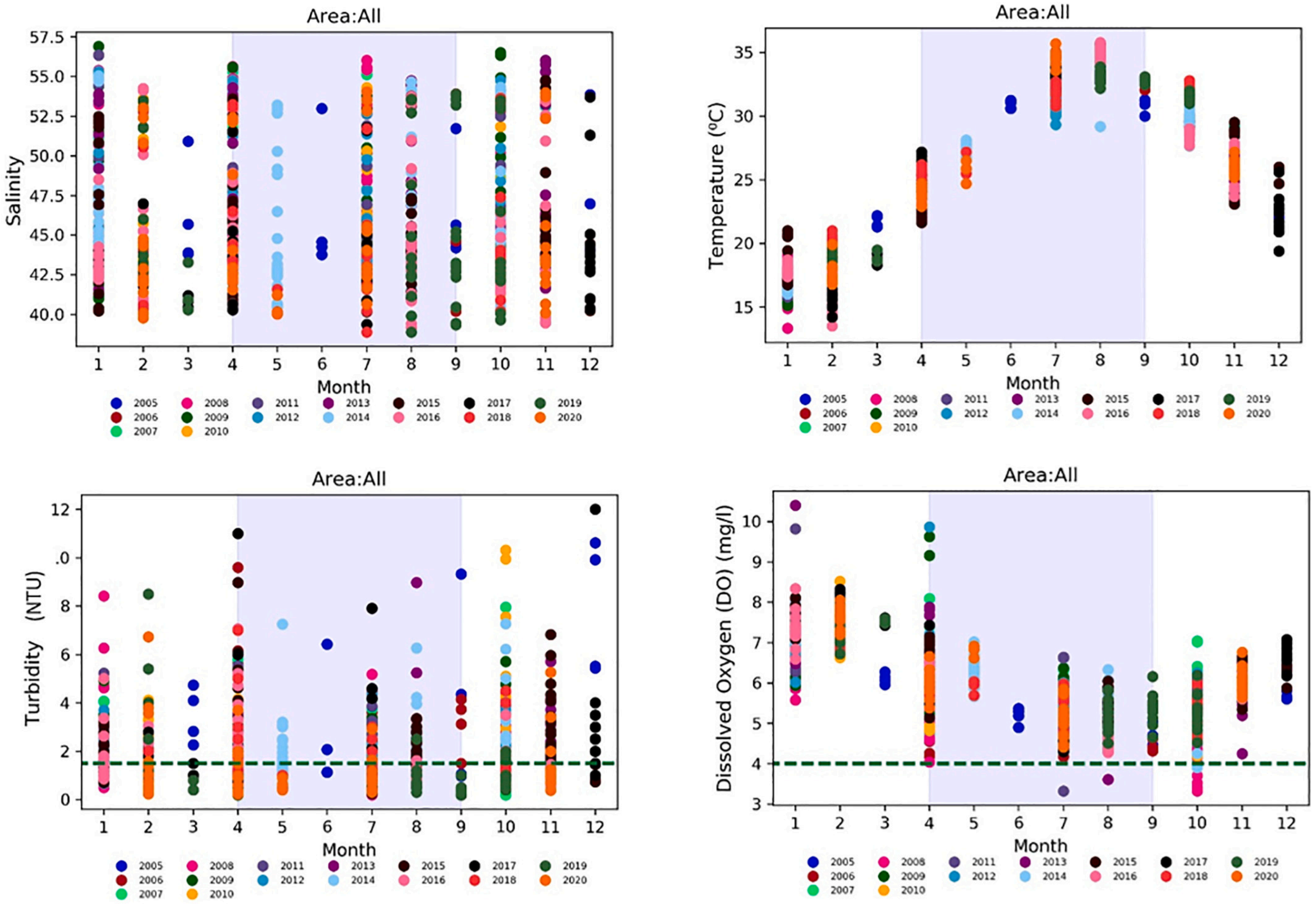


Fig. 2. Seasonal patterns in salinity, temperature, turbidity, and dissolved oxygen (DO, as mg/l) at all sites sampled. Scatterplots of all data by month. Shading indicates spring and summer (seasons 2 and 3). Dashed lines indicate one candidate threshold for turbidity (background + 50 %) and the threshold for dissolved oxygen (4 mg l^{-1}).

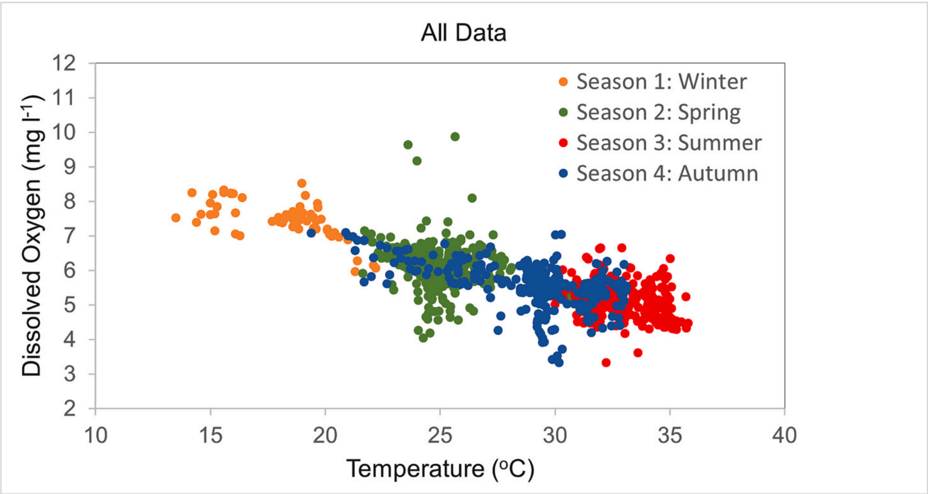


Fig. 3. Relationship between temperature and dissolved oxygen at all sites sampled.

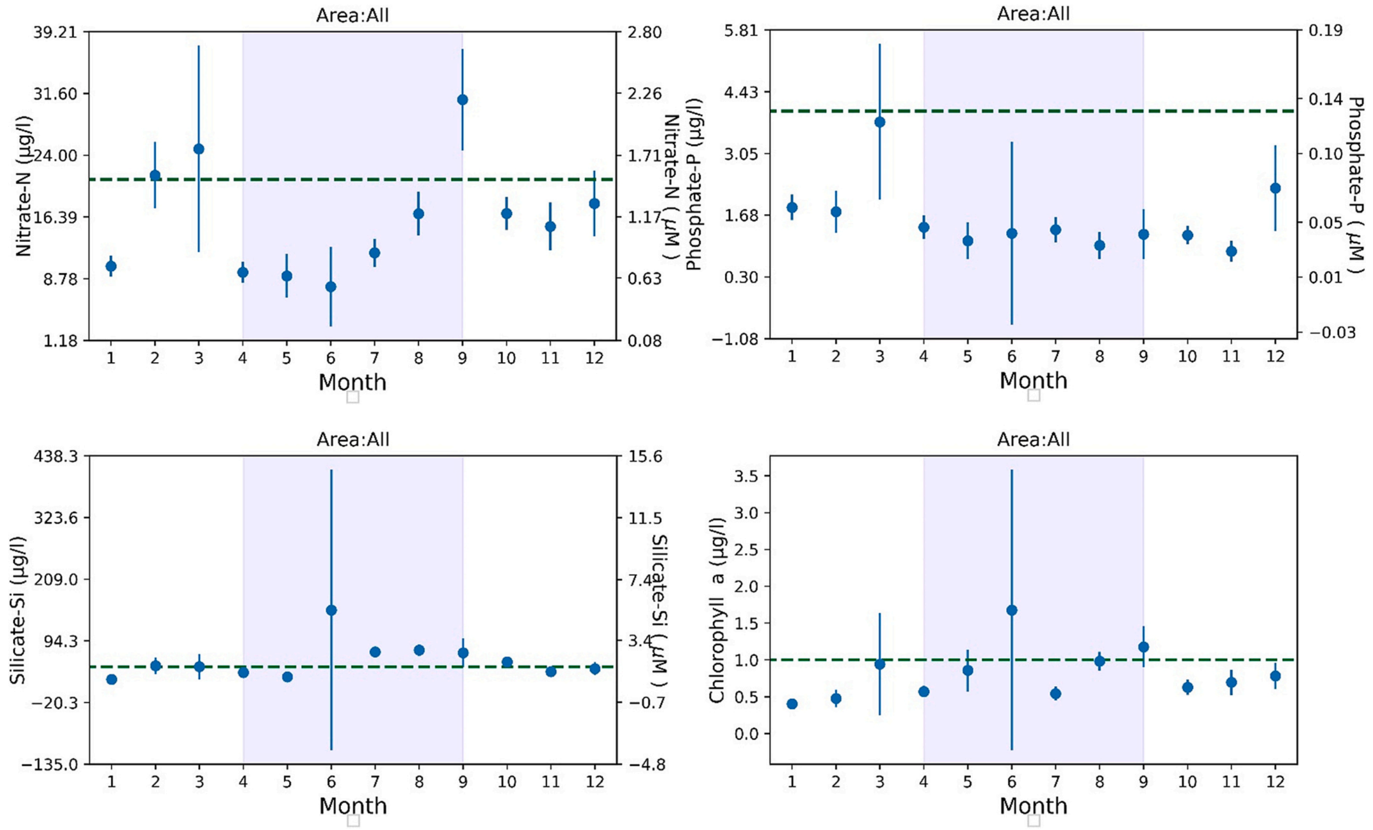


Fig. 4. Average monthly nutrient and chlorophyll concentrations at all sites sampled. Error bars show 95 % confidence intervals. Dashed lines indicate the background + 50 % candidate thresholds.

between those of the Oyster Beds and West (Fig. 5, Table 2). East and East (Coastal) had similar salinity values (42.83–44.22 and 42.46–44.17, respectively, Table 2), which were generally lower than those in West and North. No seasonal trends in salinity were evident.

Monthly averages in sea surface temperatures (Table 2) showed a narrower range in the Oyster Beds region (19.05–33.92 °C, Table 2) than in other regions, with the highest (i.e. warmest) minimum value and the lowest (i.e. coolest) maximum value. West and North had the lowest minimum values (16.54 and 16.64 °C, i.e. coldest). East (Coastal) had the highest maximum sea surface temperature (34.38 °C). Maximum values were similar in East (34.32 °C), West (34.04 °C) and North (34.32 °C). In all regions, the highest average temperature values were observed in summer (August, Table 2; Fig. 2) and lowest values in winter.

Monthly averages in turbidity and total suspended solids (TSS; Table 2) were lowest in the Oyster Beds region (0.2–1.88 NTU and 2.15–5.92 mg l^{-1}) and highest in West (0.74–6.73 NTU and 4.84–14 mg l^{-1}). Strong seasonal patterns were not evident (Table 2). For turbidity, maximum monthly averages (Table 2) were observed in autumn (December) in West (6.73 NTU, highest value), North (4.27 NTU), and Oyster Beds (1.88 NTU, lowest value) and in spring (June) or autumn (November) in East and East (Coastal) (3.78 and 4.16 NTU, respectively). For TSS, maximum monthly values (Table 2) were similar in North (8.04 mg l^{-1}, December), East (7.23 mg l^{-1}, December) and East (Coastal) waters (8.02 mg l^{-1} in April).

Monthly averages in dissolved oxygen (Table 2) were highest in the Oyster Beds region (5.41–7.72 mg l^{-1}); in other regions, all averages were above 4 mg l^{-1}. A seasonal trend (Fig. 2) was evident from monthly averages in each region, with highest values in winter (>7 mg l^{-1}, Feb/Mar, Table 2) and lowest values in summer (August/September; <5 mg l^{-1} in all regions except the Oyster Beds). These results were consistent with the seasonality in temperature described above (Section 3.1.1).

3.1.2.2. Nutrients and chlorophyll.

Monthly averages in concentrations of nitrate in the different hydrodynamic regions (Fig. 6) were generally low (<1 μM or 14 μg l^{-1}) during spring in all regions and appeared to show an increase over summer, with a possible exception in the Oyster Beds. In the East (Coastal) region, concentrations continued increasing into autumn. All regions showed high nitrate concentrations (up to *ca* 2.5 μM or 35 μg l^{-1}) in some winter months (February and/or March). High standard errors in the data, possibly due to under sampling (as described above), make it difficult to determine seasonal trends.

Monthly average nitrite concentrations were generally below 0.2 μM (*ca* 3 μg l^{-1}, Fig. S4), with no clear seasonality across areas. Higher concentrations (>0.2 μM or 3 μg l^{-1}) were measured in the East (Coastal) and East regions, particularly in late summer and autumn; high variability may be due to under sampling in some months as described above for nitrate (Section 3.1.1).

The monthly average concentrations of ammonia were generally below 1.4 μM (*ca* 20 μg l^{-1}, Fig. S5), with the Oyster Beds showing the lowest concentrations. Values were higher in East (Coastal) than in the other areas, particularly in spring and summer. Seasonal trends were not clear in any of the areas.

Monthly average DIN concentrations were generally below 50 μg l^{-1} (Fig. S6), with no clear seasonality across areas. Due to contributions by nitrate, nitrite and ammonia, higher DIN concentrations (>30 μg l^{-1}) were measured in the East (Coastal) and East regions, especially in late summer and/or autumn.

Monthly average phosphate values were generally lower than 0.1 μM (at *ca* 4 μg l^{-1}, Fig. S7) in all areas. At the Oyster Beds, monthly averages in January and March (winter) were slightly higher than 4 μg l^{-1}, possibly due to few data and/or a broad range in measured concentrations (see Fig. 7). Apart from these values, monthly phosphate averages were generally slightly higher in East (Coastal) than in other areas (Fig. S7). No seasonal patterns were evident in any of the areas.

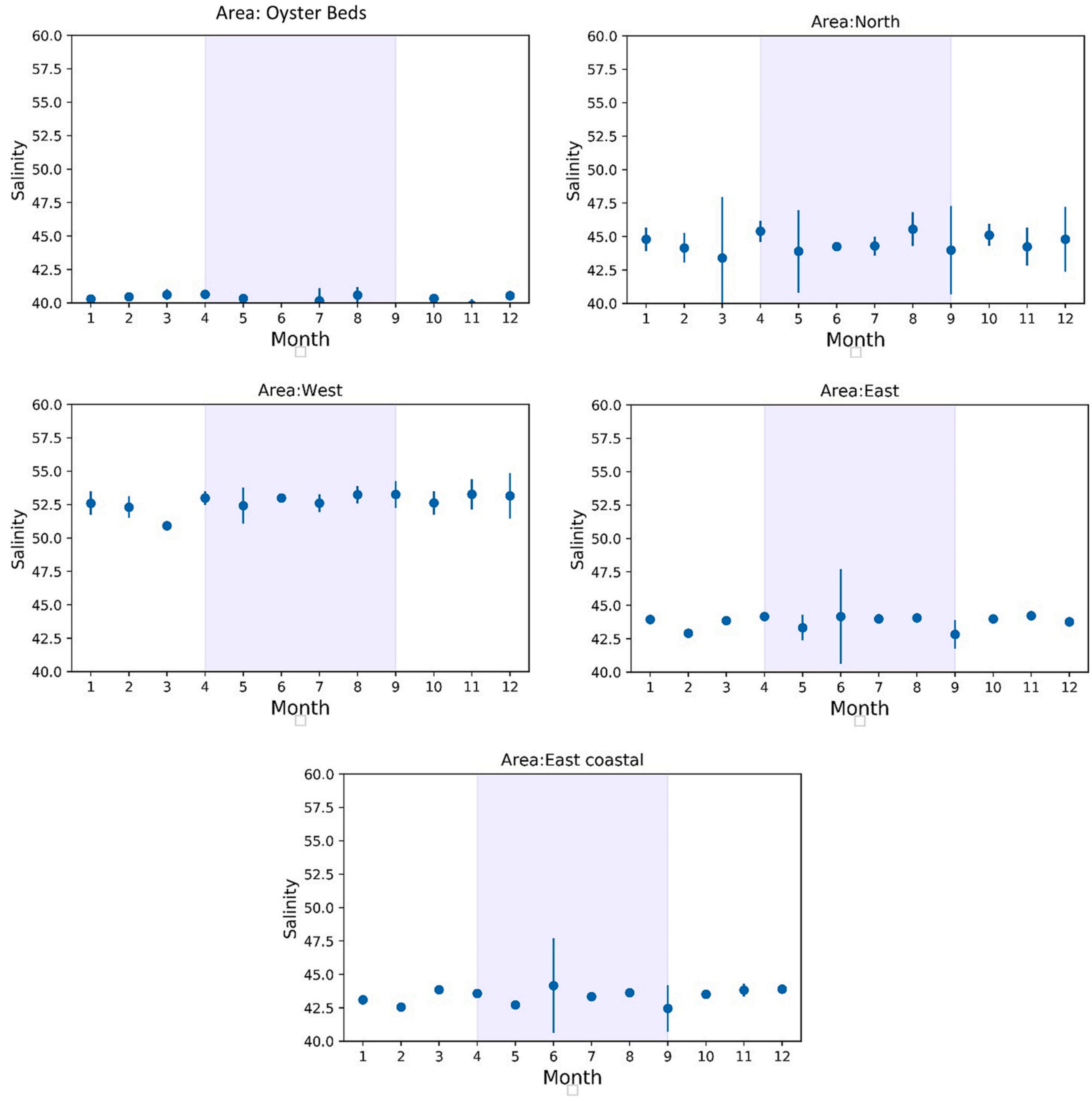


Fig. 5. Average monthly salinity concentrations for each hydrodynamic region: Oyster Beds, North, West, East and East (Coastal). Error bars show 95 % confidence intervals.

Table 2

Ranges in monthly averages (2005–2020) in salinity, temperature (°C), turbidity (NTU), total suspended solids (TSS, mg l^{-1}) and dissolved oxygen (mg l^{-1}) in each hydrodynamic region. Minimum (min) and maximum (max) values are shown, and the months in which these occurred.

Area	Salinity			Temperature (°C)			Turbidity			TSS			Dissolved oxygen (mg l^{-1})		
	Range (min–max)	Month: min value	Month: max value	Range (min–max)	Month: min value	Month: max value	Range (min–max)	Month: min value	Month: max value	Range (min–max)	Month: min value	Month: max value	Range (min–max)	Month: min value	Month: max value
Oyster Beds	39.39–40.64	Sep	Apr	19.05–33.92	Mar	Aug	0.2–1.88	Sep	Dec	2.15–5.92	Jan	Dec	5.41–7.72	Aug	Mar
North	43.39–45.55	Mar	Aug	16.64–34.19	Jan	Aug	1.4–4.27	Sep	Dec	1.8–8.04	Jun	Dec	4.93–7.61	Aug	Feb
West	50.92–53.27	Mar	Nov	16.54–34.04	Jan	Aug	0.74–6.73	Sep	Dec	4.84–14	May	Dec	4.81–7.14	Aug	Feb
East	42.83–44.22	Sep	Nov	17.24–34.32	Jan	Aug	1.49–3.78	Jul	Jun	2.0–7.23	Jun	Dec	4.98–7.57	Sep	Feb
East (coastal)	42.46–44.17	Sep	Jun	17.43–34.38	Jan	Aug	2.18–4.16	Jan	Nov	2–8.02	Jun	Apr	4.86–7.52	Sep	Feb

Monthly average silicate concentrations were generally lowest in the Oyster Beds and in North (<1.8 μM or *ca* 50 μg l^{-1}, Fig. S8). In West, East and East (Coastal) monthly averages were higher (up to approx. 10 μM, Fig. S8). Seasonal patterns were difficult to observe due to high variability in confidence levels in months when few samples were collected (March, June, September, December). If these months are excluded, highest concentrations were measured in the West region in summer.

Monthly averaged chlorophyll concentrations were generally below 1.5 μg Chl l^{-1} with no clear seasonality in any of the hydrodynamic regions (Fig. S9). At the Oyster Beds, monthly averages appeared to be higher in autumn (October, November) and in winter (February), possibly due to a broad range in a few measurements (see Fig. 7). East and East (Coastal) showed the highest averages (up to approx. 3 μg l^{-1}) in some months in winter and spring, and in autumn in East (Coastal), but the associated errors were very high.

3.2. *Development of assessment levels*

3.2.1. *Oyster Beds nutrient data*

In the Oyster Beds region, nutrient concentrations were at or below the limit of detection (LOD, Table S3) of the instrument for most samples analysed for nitrite (83.3 %), ammonia (60 %) and phosphate (58 %). For nitrate, 45 % of samples were at or below the LOD. Silicate was the nutrient with the smallest number of samples (5 %) at or below the LOD.

Average concentrations (2014–2020) from the four Oyster Beds sites (Table 3), calculated to represent near-pristine background conditions, were low for most nutrients and chlorophyll, i.e. 0.97 μM for nitrate, 0.07 μM for nitrite, 0.36 μM for ammonia, 0.08 μM for phosphate and 0.7 μg Chl l^{-1}. Average concentrations above 1 μM were observed for silicate (1.09 μM) and DIN (1.45 μM). The 95th percentile values were higher (e.g. 3.3 μM nitrate, 3.57 μM DIN and 2.12 μM silicate).

3.2.2. *Candidate thresholds*

All in situ monitoring data from the Oyster Beds region were plotted with all three candidate thresholds developed from these data (Fig. 7), for visual comparisons of data and thresholds. As expected, most data points fell below the 95th percentile (top line, Fig. 7), and the candidate thresholds based on 100 % deviation from background (middle line, Fig. 7) were higher than those based on 50 % deviation from background (bottom line, Fig. 7).

For most nutrients (nitrate, nitrite, ammonia, phosphate), candidate thresholds based on 50 % and 100 % deviation from background conditions (Table 3) were similar. For example, for nitrate the candidate thresholds were 1.45 μM (equivalent to 20.27 μg l^{-1}) for 50 % deviation from background, and 1.93 μM (27.02 μg l^{-1}) for 100 % deviation from background. Candidate thresholds using the 95th percentile were up to two times higher: for example, for nitrate the 95th percentile threshold was 3.3 μM nitrate (46.17 μg l^{-1}, Table 3).

For silicate, larger differences were observed between candidate thresholds based on 50 % deviation from background (46.1 μg l^{-1}) and 100 % deviation from background (61.46 μg l^{-1}, Table 3). The candidate threshold using the 95th percentile (59.55 μg l^{-1}) was lower than the threshold using 100 % deviation from background.

For chlorophyll, candidate thresholds based on 50 % and 100 % deviation from background conditions (Table 3) were similar (1.05 vs 1.4 μg Chl l^{-1}). The candidate threshold using the 95th percentile was up to 60 % higher (1.76 μg Chl l^{-1}).

For total suspended solids (TSS, Table 3), larger differences were observed between candidate thresholds based on 50 % variation from background (6.22 mg l^{-1}) and 100 % variation from background (8.3 mg l^{-1}, 25 % higher). The candidate threshold using the 95th percentile (8.9 mg l^{-1}) was similar to but slightly higher than the threshold using 100 % deviation from background.

For turbidity, levels increased by approximately 0.5 turbidity units across candidate thresholds (Table 3): from 1.53 NTU (50 % variation from background) to 2.03 NTU (100 % variation from background) to

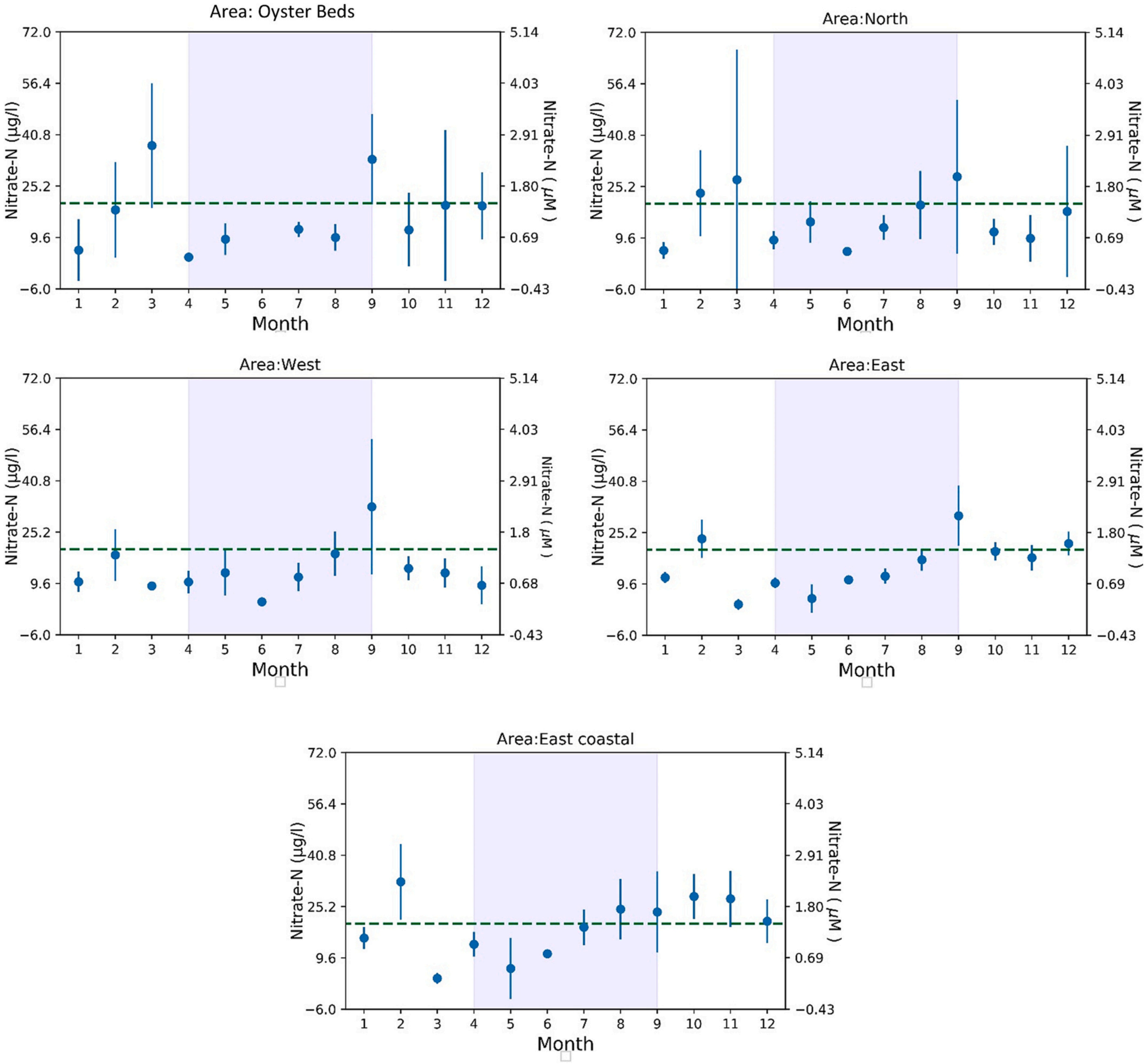


Fig. 6. Monthly averages in nitrate concentrations in the different areas. Dashed lines indicate the background + 50 % candidate threshold.

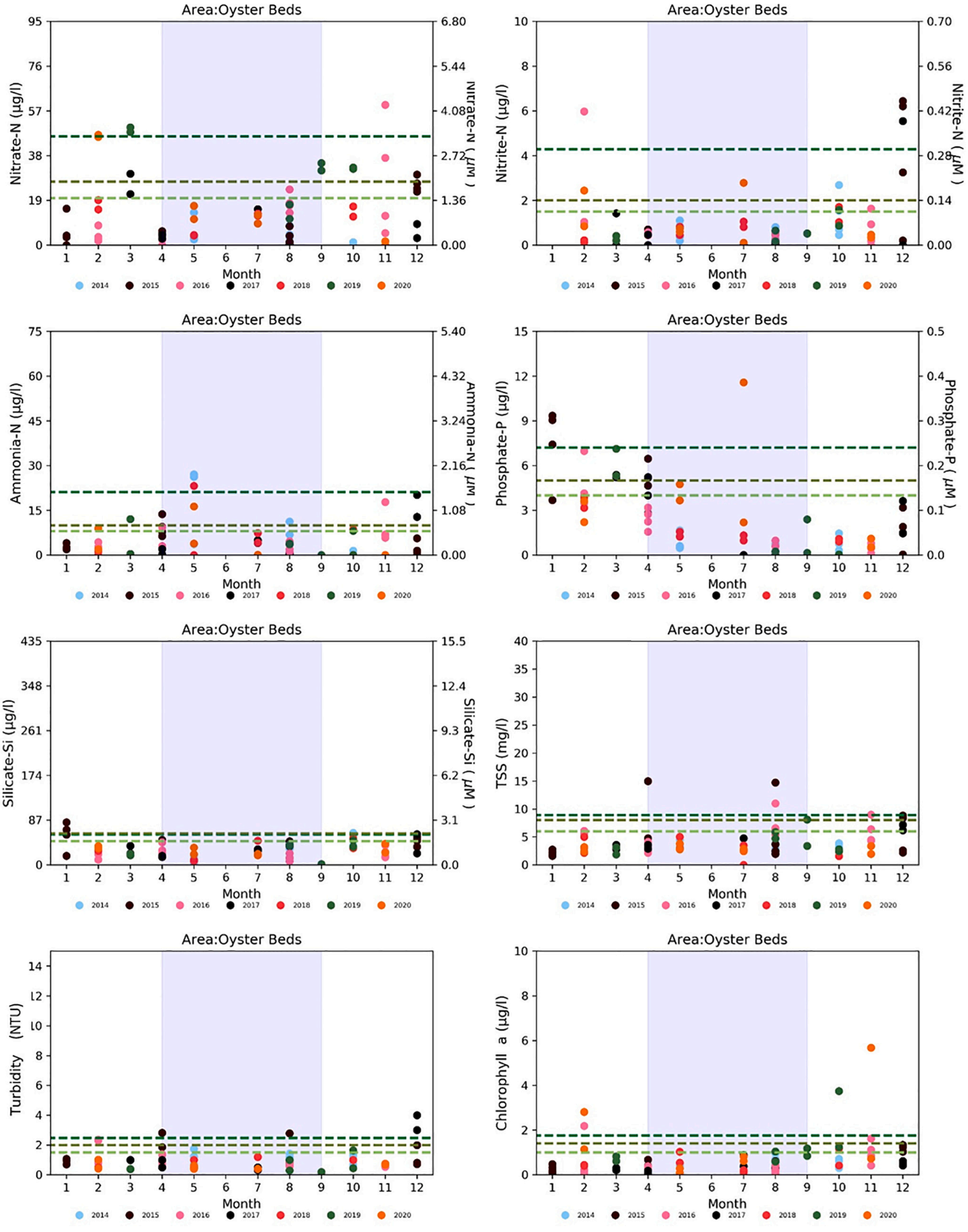


Fig. 7. Data from the Oyster Beds area showing all options for thresholds (95th percentiles, 100 % and 50 % above the mean). Dashed lines indicate all candidate thresholds (top = 95th percentile, middle = background + 100 %, bottom = background + 50 %).

Table 3

Background values of nutrients and chlorophyll in Bahrain's waters, calculated as averages and 95th percentiles using data (2014–2020) from the four Oyster Beds sites. These values were used to determine candidate thresholds: (a) allowing for 50 % deviation from average background values; (b) allowing for 100 % deviation from average background values; (c) the 95th percentiles. Thresholds were taken from the literature for dissolved oxygen (Best et al., 2007) and DIN:DIP (based on 50 % deviation from the Redfield Ratio, Downing, 1997). For DIN:DIP, background values were calculated using phosphate-P data above the limit of detection (LOD, 0.06 μM).

	LOD	Background values				Candidate thresholds						Literature thresholds
		Average		95%ile		(a) 50 % deviation from average		(b) 100 % deviation from average		(c) 95%ile		
Parameter	*μg* l^{-1}	*μg* l^{-1}	*μM*	*μg* l^{-1}	*μM*	*μg* l^{-1}	*μM*	*μg* l^{-1}	*μM*	*μg* l^{-1}	*μM*	
Nitrate-N	6	13.51	0.97	46.17	3.3	20.27	1.45	27.02	1.93	46.17	3.3	
Nitrite-N	1.5	0.96	0.07	4.29	0.31	1.44	0.1	1.92	0.14	4.29	0.31	
Ammonia-N	4	5.06	0.36	21.11	1.5	7.59	0.54	10.12	0.7	21.11	1.5	
Phosphate-P	2	2.35	0.08	7.2	0.23	3.52	0.12	4.72	0.15	7.2	0.23	
Silicates-Si	7	30.73	1.09	59.55	2.12	46.1	1.64	61.46	2.19	59.55	2.12	
DIN		20.24	1.45	49.99	3.57	30.35	2.17	40.72	2.9	49.99	3.57	
Chlorophyll		0.7	–	1.76	–	1.05	–	1.4	–	1.76	–	
DIN: DIP		13.62		34.88		20.43		27.25		34.88		24
Parameter		*mg* l^{-1}		*mg* l^{-1}		*mg* l^{-1}		*mg* l^{-1}		*mg* l^{-1}		*mg* l^{-1}
Dissolved Oxygen		6.27	–	7.54	–		–		–	7.54	–	4
TSS		4.15	–	8.9	–	6.22	–	8.3	–	8.9	–	
Parameter		*NTU*		*NTU*		*NTU*		*NTU*		*NTU*		
Turbidity		1.02	–	2.48	–	1.53	–	2.03	–	2.48	–	

2.48 NTU (95th percentile).

As described in the Methods section, thresholds derived from the literature were used for dissolved oxygen and N:P ratios (Table 3).

3.3. Long-term and annual averages and 95th percentiles; comparisons against candidate thresholds

3.3.1. Long-term averages and 95th percentiles per region

Long-term averages (2014–2020) in the Oyster Beds region (Table 4, column i) showed the lowest values (shaded grey, Table 4) for ammonia, DIN:DIP, silicate, total suspended solids and turbidity; dissolved oxygen levels were highest here. Long-term averages in North (2005–2020) were similar to those in the Oyster Beds and lowest for nitrate and nitrite (Table 4).

The East (Coastal) region had the highest long-term (2005–2020) average concentrations (Table 4) for all nutrient parameters (except silicate) and chlorophyll. In the broader East region, values were lower than in East (Coastal) but still relatively high (Table 4), presumably due to the influence of the inshore sites. East (Coastal) and West had the lowest long-term average concentrations for dissolved oxygen (5.95 and 5.86 mg l^{-1}, respectively, Table 4).

The West region showed the lowest long-term averages (2005–2020, Table 4) for phosphate (0.62 μg l^{-1}) and chlorophyll (0.54 μg Chl l^{-1}). Silicate concentrations were highest (61.77 μg l^{-1}) here.

The 95th percentiles (2005–2020) for most parameters in each hydrodynamic region were two to five times higher than the average values (Table 4). The main exception was dissolved oxygen, for which 95th percentiles were only slightly higher than the average values.

3.3.2. Comparisons of long-term averages and 95th percentiles per region against candidate thresholds

Comparisons of long-term data per region against each of the candidate thresholds showed that the Oyster Beds compared most favourably (Table 4, Fig. 8). As expected, all averages (2014–2020) at the Oyster Beds were below the candidate thresholds based on 50 % and 100 % variation from background. Using the 95th percentile candidate threshold, DIN:DIP exceeded (i.e. was higher than) the threshold (24) derived from the literature (grey shading, Fig. 8). For TSS, the 95th percentile was the same as the candidate threshold (8.9 mg l^{-1}, Table 4, yellow shading Fig. 8).

In the North region, all averages (2005–2020) were also below the candidate thresholds based on 50 % and 100 % variation from background (Fig. 8, Table 4). The 95th percentile for DIN:DIP here also exceeded the threshold (24) derived from the literature. In addition, the 95th percentiles for three other parameters (silicate, TSS, turbidity) exceeded the 95th percentile candidate threshold.

In West, East and East (Coastal), three to five parameters exceeded the 50 % candidate threshold and four to eight exceeded the 95th percentile candidate threshold (Fig. 8, Table 4). Comparisons against the 100 % candidate threshold showed that the number of exceedances were: none in East, one in West (silicate), and three in East (Coastal) (nitrite, ammonia, turbidity).

3.3.3. Averages and 95th percentiles per year in each region

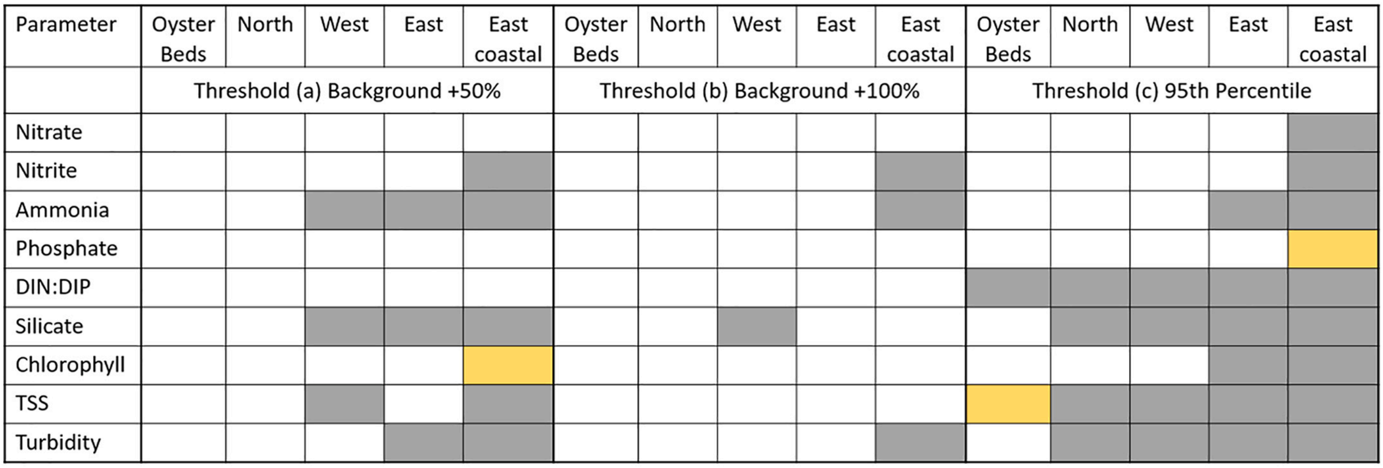
In each hydrodynamic region, averages per year (i.e. annual averages) were also compared against candidate thresholds (e.g. Fig. 9, East (Coastal)). The fewest exceedances were generally observed when the 100 % candidate threshold was used (Table 4; detail given in Table S4). In the Oyster Beds region (2014–2020), the 100 % candidate threshold was exceeded in one year by nitrate (2019) and by chlorophyll (2020; Table 4, Table S4). In all other years, annual averages for all parameters were below the 100 % candidate threshold. The 50 % threshold was exceeded once, in different years, by four nutrients (nitrate in 2019, nitrite in 2015, ammonia in 2014, phosphate in 2020) and in two years (2019, 2020) by chlorophyll (Table 4, Table S4). The 95th percentile candidate threshold was exceeded in one year by nitrite (2015) and ammonia (2014) and in two years by most other parameters (Table 4, Table S4).

Similarly, in other regions candidate thresholds were exceeded in some individual years (Table 4, Table S4). The greatest number of exceedances in annual averages was observed in East (Coastal) (Fig. 9). The 50 % candidate thresholds (shown in Fig. 9) were exceeded for nitrate in eight years (2011, 2014–2020), for nitrite and ammonia in almost all years, for phosphate in four years (2005, 2008, 2011, 2020), for silicate in almost all years and for chlorophyll in more than half of the years. The 100 % thresholds were generally exceeded in fewer years than the 50 % thresholds (Table 4, Table S4). The number of exceedances of the 95th percentile threshold was generally greater than the number of exceedances of the 50 % threshold (Table 4, Table S4). Exceptions were for nitrite and ammonia, which exceeded the 50 % threshold more often than the 95th percentile threshold (Table 4, Table S4). In other hydrodynamic regions, the number of exceedances was also

Table 4

Averages, 95th percentiles, long-term trends and comparisons against candidate thresholds in each hydrodynamic region, using data from 2014 to 2020 for Oyster Beds and 2005–2020 for all other regions. (i) Averages (avg) and 95th percentiles (95%ile), and significant increasing (↗) or decreasing (↘) trends in averages; see Table S4 for standard errors. (ii) Candidate thresholds a, b and c calculated from Oyster Beds data (2014–2020). (iii) Averages and 95th percentiles (2005/2014–2020) above the candidate thresholds (Y = yes; ~ = value on the threshold; blank = no); summarised in Fig. 8. (iv) Number of individual years 2005–2020 (N) with averages or 95th percentiles above the candidate thresholds (see Supplementary Table S4 for details). n = total number of data points. Dissolved oxygen (DO) results are not shown, because values above the threshold are desirable. Shading = lowest averages for each parameter. * = comparisons of 95th percentile values against threshold (c) are not recommended as good practice. Thresholds for DIN:DIP and dissolved oxygen were derived from the literature (see Methods).

	Parameter	**(i) All data from 2005-2020** (Oyster Beds data from 2014 only)				**(ii) Candidate Thresholds**			**(iii) Averages or 95%iles above the candidate thresholds?**			**(iv) Number of individual years 2005-2020 (N) with parameters above candidate thresholds**		
		n	**Avg**	**Trend (in Avg)**	**95 %ile**	**(a) Backgr +50%**	**(b) Backgr +100%**	**(c) 95 %ile**	**Avg above threshold (a) +50%**	**Avg above threshold (b) +100%**	***95 %iles above threshold (c) 95%ile**	**N with avgs above threshold (a) 50%**	**N with avgs above threshold (b) 100%**	***N with 95 %iles above threshold (c) 95%ile**
Oyster Beds	Nitrate-N (μg l^{-1})	76	13.51	↗	46.17	20.27	27.02	46.17				1	1	2
	Nitrite-N (μg l^{-1})	72	0.96		4.29	1.44	1.92	4.29				1		1
	Ammonia-N (μg l^{-1})	75	5.06		21.11	7.59	10.12	21.11				1		1
	Phosphate-P (μg l^{-1})	76	2.35		7.2	3.52	4.7	7.2				1		2
	DIN:DIP	29	13.62		34.89	24	24	24			Y			
	Silicate-Si (μg l^{-1})	76	30.73		59.55	46.1	61.46	59.55						2
	Chlorophyll (μg l^{-1})	76	0.7		1.76	1.05	1.4	1.76				2	1	2
	DO (mg l^{-1})	76	6.27		7.55	4	4	4	-	-	-	-	-	-
	TSS (mg l^{-1})	76	4.15		8.9	6.22	8.3	8.9						2
	Turbidity (NTU)	76	1.02		2.48	3.52	2.03	2.48			~			2
North	Nitrate-N (μg l^{-1})	168	12.9		37.5	20.27	27.02	46.17				2	1	3
	Nitrite-N (μg l^{-1})	166	0.71		1.76	1.44	1.92	4.29						
	Ammonia-N (μg l^{-1})	168	7.28		19.96	7.59	10.12	21.11				5	3	3
	Phosphate-P (μg l^{-1})	165	0.97		2.68	3.52	4.7	7.2						1
	DIN:DIP	19	17.42		42.36	24	24	24			Y			
	Silicate-Si (μg l^{-1})	168	32.29	↘	90.77	46.1	61.46	59.55			Y	3	1	6
	Chlorophyll (μg l^{-1})	167	0.57		1.36	1.05	1.4	1.76				1		1
	DO (mg l^{-1})	163	6.07		7.69	4	4	4	-	-	-	-	-	-
	TSS (mg l^{-1})	167	5.63	↘	13.81	6.22	8.3	8.9			Y	7	1	10
	Turbidity (NTU)	168	1.91	↘	4.34	1.53	2.03	2.48			Y	10	5	13
West	Nitrate-N (μg l^{-1})	250	13.14		43.68	20.27	27.02	46.17				2	1	1
	Nitrite-N (μg l^{-1})	250	1.1		3	1.44	1.92	4.29				6	2	1
	Ammonia-N (μg l^{-1})	248	7.67		20.5	7.59	10.12	21.11	Y			4	2	2
	Phosphate-P (μg l^{-1})	245	0.62		2.12	3.52	4.7	7.2						
	DIN:DIP	17	13.7		30.79	24	24	24			Y			
	Silicate-Si (μg l^{-1})	250	61.77		170.96	46.1	61.46	59.55	Y	Y	Y	16	9	16
	Chlorophyll (μg l^{-1})	249	0.54		1.55	1.05	1.4	1.76				1	1	1
	DO (mg l^{-1})	249	5.86		7.38	4	4	4	-	-	-	-	-	-
	TSS (mg l^{-1})	250	6.64		15.51	6.22	8.3	8.9	Y		Y	7	5	13
	Turbidity (NTU)	250	1.65		3.52	3.52	2.03	2.48			Y	8	4	9
East	Nitrate-N (μg l^{-1})	642	14.5	↗	43.22	20.27	27.02	46.17				4	1	2
	Nitrite-N (μg l^{-1})	648	1.36		4.07	1.44	1.92	4.29				7	3	3
	Ammonia-N (μg l^{-1})	655	9.08		26.74	7.59	10.12	21.11	Y		Y	11	7	10
	Phosphate-P (μg l^{-1})	647	1.72		5.69	3.52	4.7	7.2				1	1	4
	DIN:DIP	205	21.47		47.5	24	24	24			Y			
	Silicate-Si (μg l^{-1})	655	50.64		134.67	46.1	61.46	59.55	Y		Y	8	3	16
	Chlorophyll (μg l^{-1})	653	0.66		2.12	1.05	1.4	1.76			Y	4	2	9
	DO (mg l^{-1})	654	6.02		7.76	4	4	4	-	-	-	-	-	-
	TSS (mg l^{-1})	657	5.55		12.22	6.22	8.3	8.9			Y	5	8	14
	Turbidity (NTU)	657	1.99		5.25	1.53	2.03	2.48	Y		Y	14	16	16
East (coastal)	Nitrate-N (μg l^{-1})	200	20.25	↗	51.88	20.27	27.02	46.17			Y	8	4	9
	Nitrite-N (μg l^{-1})	201	1.97		4.79	1.44	1.92	4.29	Y	Y	Y	13	9	7
	Ammonia-N (μg l^{-1})	203	12.55		33.51	7.59	10.12	21.11	Y	Y	Y	15	12	12
	Phosphate-P (μg l^{-1})	201	3.3		7.2	3.52	4.7	7.2			~	4	2	5
	DIN:DIP	145	22.72	↗	49.35	24	24	24			Y			
	Silicate-Si (μg l^{-1})	204	61.07		149.4	46.1	61.46	59.55	Y		Y	12	6	16
	Chlorophyll (μg l^{-1})	201	1.05		3.15	1.05	1.4	1.76	~		Y	9	6	13
	DO (mg l^{-1})	202	5.95		7.72	4	4	4	-	-	-	-	-	-
	TSS (mg l^{-1})	204	6.63		13.5	6.22	8.3	8.9	Y		Y	11	1	15
	Turbidity (NTU)	204	2.93		6.81	1.53	2.03	2.48	Y	Y	Y	16	16	16



Parameter	Oyster Beds	North	West	East	East coastal	Oyster Beds	North	West	East	East coastal	Oyster Beds	North	West	East	East coastal
	Threshold (a) Background +50%					Threshold (b) Background +100%					Threshold (c) 95th Percentile				
Nitrate															▨
Nitrite					▨					▨					▨
Ammonia			▨	▨	▨					▨				▨	▨
Phosphate															🟨
DIN:DIP											▨	▨	▨	▨	▨
Silicate			▨	▨	▨			▨				▨	▨	▨	▨
Chlorophyll					🟨									▨	▨
TSS			▨		▨						🟨	▨	▨	▨	▨
Turbidity				▨	▨					▨		▨	▨	▨	▨

Fig. 8. Summary of where averages and 95th percentiles over the whole period (2005–2020) exceeded candidate thresholds (grey shading; see Table 4, column iii). Yellow shading indicates where averages or percentiles were the same as the candidate threshold.

occasionally greater for the 50 % threshold than the 95th percentile threshold (e.g. in North for ammonia; in West for nitrate, nitrite and ammonia; in East for nitrate, nitrite and ammonia; Table 4, Table S4).

Overall, based on the number of exceedances of candidate thresholds, annual averages indicated better water quality in the Oyster Beds than in other areas, and that the sites in this region may indeed represent pristine conditions. The East (Coastal) area presented the lowest standards of water quality.

3.3.4. *Long-term averages by site*

Long-term averages by site (Table 5) showed that six sites (three in the Oyster Beds, three in the offshore waters in East) had no parameters which exceeded the candidate thresholds based on 50 % variation from background. At all other sites, the candidate thresholds were exceeded for one to nine parameters (Table 5). In the Oyster Beds, only ammonia exceeded the threshold, at Najwat Abu Lthama. The sites with the greatest number of exceedances (4–9) were in East (Coastal), i.e. Askar, Gaha, Suhain and Refinery (Table 5); chlorophyll exceeded the threshold only in East (Coastal), at Askar and Refinery. At most sites, the parameters which most frequently exceeded the threshold were turbidity, ammonia and silicate (Table 5).

The 100 % candidate threshold was exceeded at fewer sites than the 50 % candidate threshold. In the Oyster Beds, no parameters exceeded the threshold (Table 5). The sites with the greatest number of exceedances (>2) were in East (Coastal), i.e. Askar and Refinery (Table 5); chlorophyll exceeded the threshold only in East (Coastal), at Askar and Refinery. The parameters which most frequently exceeded the threshold were turbidity, ammonia and silicate (Table 5).

3.4. *Trends*

3.4.1. *Significant trends by region*

Significant long-term trends for water quality were observed in one to three parameters in all regions apart from West (indicated by arrows, Table 4). In the Oyster Beds, nitrate showed a significant increasing trend. In the North region, silicate, TSS and turbidity showed significant downward trends. In the East, nitrate showed a significant increasing trend. In East (Coastal), nitrate and DIN:DIP showed significant increasing trends.

3.4.2. *Significant trends by site*

Trends analysed by site (Table 6) showed increasing trends in nutrient concentrations (usually nitrate, DIN and/or DIN:DIP) at one site in the Oyster Beds (Shtaya), two sites in the West (Umm Al Na'asan and Ya'suf), four sites in East and three sites in East (Coastal).

Decreasing trends were observed at one site in the Oyster Beds region (Abu Lthama, salinity), two sites in North (salinity and silicate; turbidity and phosphate), three sites in West (in salinity at all three sites, in temperature at one site), six sites in East (salinity at all, phosphate at one, silicate at one, nitrite at one), and at two sites in East (Coastal) (salinity at both, ammonia at one).

Chlorophyll showed an increasing trend at Umm Al Na'asan (West) and at Jaradah (East), possibly reflecting significant increasing trends in nitrate and/or DIN here. Dissolved oxygen showed no significant trends at any of the sites.

3.4.3. *Seasonal trends at site level*

Data (2005/14–2020) were averaged by season at each site to identify seasonal patterns and trends (Table 7). For example, at Ya'suf (West, Fig. S10), water temperatures were consistently highest in summer and lowest in winter. Trend analysis showed significant increasing trends (Ya'suf, Table 7) in summer for temperature and chlorophyll, and in autumn in DIN. Significant decreasing trends were observed in winter for turbidity, in spring for phosphate and in summer for dissolved oxygen (decreasing consistently with the significant increase in temperature).

Only two of the four Oyster Beds sites had time series long enough to calculate trends: Abu Lthama and Shtaya. Only Shtaya showed any significant trends, viz. a significant increasing trend for winter chlorophyll, possibly due to increased DIN (Table 6) but not explained by significant changes in nutrients or turbidity, or at a level high enough to exceed candidate thresholds.

At other sites with sufficient data for analysis, a significant increasing trend in temperature was consistently observed in summer (Table 7).

Patterns in the significant seasonal trends were not clear for other parameters at other sites, although some similarities could be found (Table 7). For instance, dissolved oxygen showed significant increasing trends in winter for three sites (Al Jasra, Umm al Na'asan and Ya'suf, all in the West) and significant decreasing trends in summer for two sites (Murwada, North, and Ya'suf, West). TSS showed significant changes at two East (Coastal) sites (increasing in winter at Refinery and decreasing in spring at Gaha) and at one offshore site in East (decreasing at Noon). Turbidity showed significant trends at different sites in every season: decreasing in winter in Al Jasra and Ya'suf (West) and Jabari (East); increasing in spring at Gasar (West), and Gazara, Jaradah and Mashtan (East); decreasing in summer at Murwada (North) and Al Jasra (West),

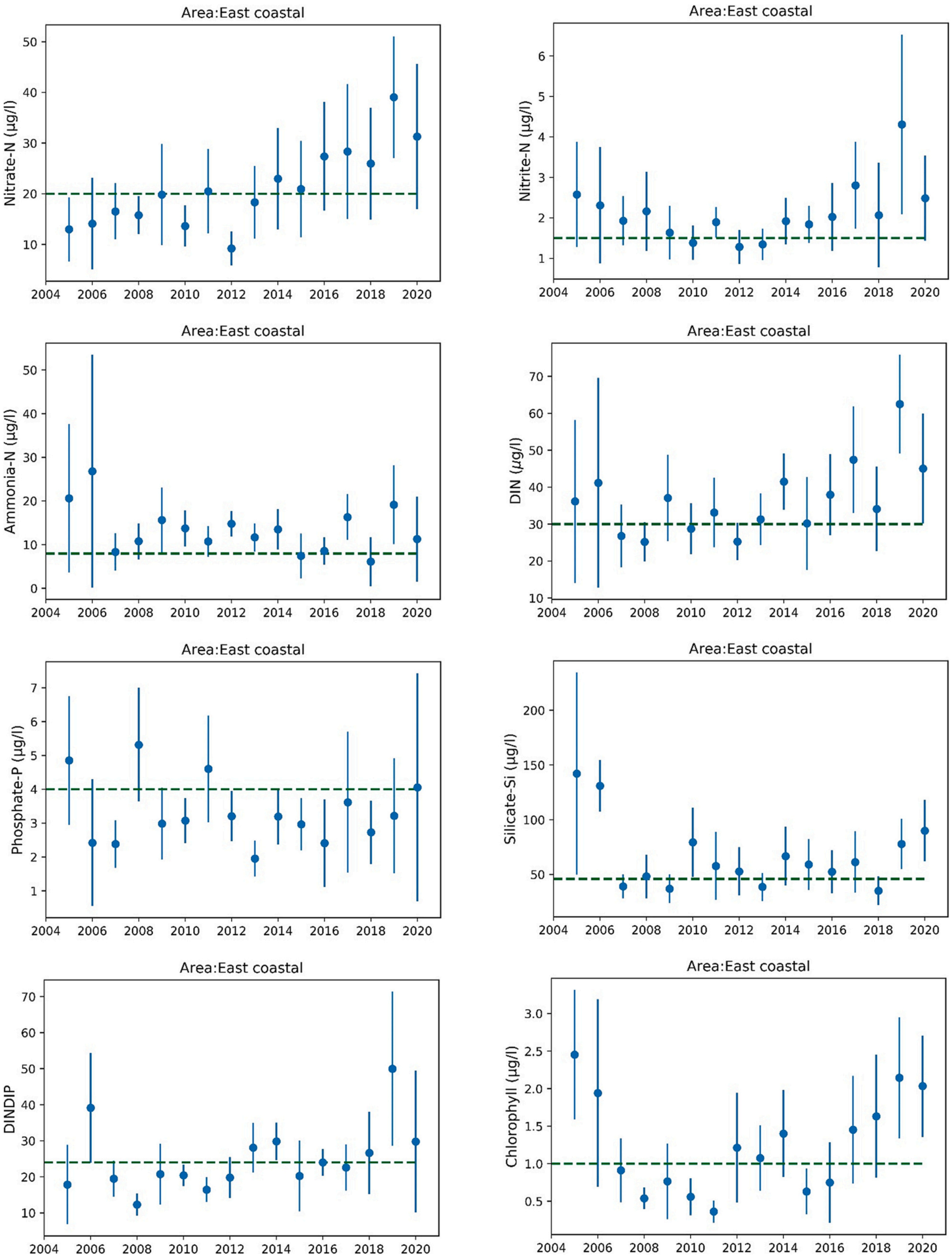


Fig. 9. Average annual nutrient and chlorophyll concentrations in the East (Coastal) region. Error bars show 95 % confidence intervals. Dashed lines indicate the background + 50 % candidate thresholds.

Table 5
Sites in each hydrodynamic region where averages (2005/2014–2020) exceeded candidate thresholds using 50 % and 100 % variation from background. The approach used is the same as in Table 4. If sites and parameters are not shown here, then their average value (2005/2014–2020) did not exceed the threshold value. n = number of parameters which exceeded the threshold at each site.

Region	Site	Threshold a (backgr + 50 %)		Threshold b (backgr + 100 %)	
		n	Parameters with averages above threshold a	n	Parameters with averages above threshold b
Oyster Beds	Najwat Abu Lthama	1	Ammonia		
North	West Jarim	4	Turbidity, TSS, nitrate, DIN	1	Turbidity
	Khorfasht	3	Turbidity, TSS, ammonia	1	Turbidity
	Murwada	2	Turbidity, TSS,		
	Al-Jarim	1	Turbidity		
West	Al-Jasra	4	Turbidity, TSS, ammonia, silicate	2	Turbidity, silicate
	Bartafi	4	Turbidity, TSS, nitrate, DIN		
	Gasar	3	TSS, ammonia, silicate	1	Silicate
	Ya'suf	3	Turbidity, TSS, silicate	1	Silicate
	Umm Al Na'asan	1	Silicate	1	Silicate
East (beyond coastal waters)	Jabari	4	Turbidity, ammonia, silicate, DIN:DIP	1	DIN:DIP
	Noon	4	Turbidity, nitrite, ammonia, silicate	2	Nitrite, silicate
	Msoor	3	Turbidity, ammonia, silicate	1	Turbidity
	Tugailib	3	Ammonia, silicate, DIN:DIP	1	DIN:DIP
	Ghumais:	2	Turbidity, TSS		
	Mashtan	2	Silicate, DIN:DIP	1	DIN:DIP
	Duwaimil:	1	Ammonia		
East (coastal)	Refinery	9	Turbidity, TSS, nitrate, nitrite, ammonia, DIN, DIN:DIP, silicate, chlorophyll	7	Turbidity, nitrite, ammonia, DIN, DIN:DIP, silicate, chlorophyll
	Suhain:	7	Turbidity, nitrate, nitrite, ammonia, DIN, silicate, phosphate	2	Turbidity, ammonia
	Askar	6	Turbidity, TSS, nitrite, ammonia, silicate, chlorophyll	3	Turbidity, ammonia, silicate
	Gaha	4	Turbidity, nitrate, ammonia, DIN		

Table 6
Summary of significant trends (2005–2020) per site, from Mann-Kendall analyses of averages per year. DIN = dissolved inorganic nitrogen, DIP = dissolved inorganic phosphorus, – no significant trend observed.

Site	Area	Increasing trends	Decreasing trends
Abu Lthama	Oyster Beds	–	Salinity
Bo Omamah	Oyster Beds	–	–
Najwat Abu Lthama	Oyster Beds	–	–
Shtaya	Oyster Beds	DIN, DIN:DIP	–
Al Jarim	North	–	Salinity, Silicate
Khorfasht	North	–	Turbidity, Phosphate
Murwada	North	–	–
West Jarim	North	–	–
Al Jasra	West	–	–
Bartafi	West	–	–
Gasar	West	–	Salinity, Temperature
Umm Al Na'asan	West	Chlorophyll, Nitrate	Salinity
Ya'suf	West	DIN	Salinity
Dam	East	–	–
Duwaimil	East	–	–
Gazara	East	–	Salinity
Ghumais	East	Nitrate, DIN	Salinity, Phosphate
Jabari	East	–	Salinity
Jaradah	East	Chlorophyll, Nitrate, DIN	Salinity
Mashtan	East	Nitrate, DIN	Salinity, Silicate
Msoor	East	–	–
Noon	East	DIN	–
Tugailib	East	–	Salinity, Nitrite
Askar	East (coastal)	Nitrate	Salinity
Gaha	East (coastal)	–	–
Refinery	East (coastal)	Nitrate	Salinity, Ammonia
Suhain	East (coastal)	Nitrite, DIN, DIN:DIP	–

Table 7

Summary of significant trends by season in eight parameters per site, from Mann-Kendall analyses of averages per season (1–4). ↘ = decreasing trend, ↗ = increasing trend, – = insufficient data, blank = no significant trend observed. DO = dissolved oxygen, TSS = total suspended solids, DIN = dissolved inorganic nitrogen. Season 1 = winter, Season 2 = spring, Season 3 = summer, Season 4 = autumn. Data from all seasons were analysed at all sites apart from the three with insufficient data, but results are only shown for seasons with one or more significant trends.

	Sites	Temperature	DO			TSS		Turbidity				DIN				Phosphate-P				Silicate-Si			Chlorophyll a			
	Season	3	1	2	3	1	2	1	2	3	4	1	2	3	4	1	2	3	4	2	3	4	1	2	3	4
Oyster Beds	Abu Lthama																									
	Bo Omamah	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Najwat Abu Lthama	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Shtaya																						↗			
North	Al-Jarim	↗														↘			↘		↗					
	Khorfasht	↗																↘								
	Murwada	↗			↘					↘																
	West Jarim	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
West	Al Jasra	↗	↗					↘		↘	↘															
	Bartafi	↗											↘				↘		↘							
	Gasar	↗							↗															↗		
	Umm Al Na'asan	↗	↗																							↗
	Ya'suf	↗	↗		↘			↘							↗		↘								↗	
East	Askar	↗										↗														
	Dam	↗													↘											
	Duwaimil	↗								↗																
	Gaha	↗					↘																			
	Gazara	↗							↗											↗						↗
	Ghumais	↗										↗		↗												
	Jabari	↗						↘				↗														
	Jaradah	↗							↗																↗	
	Mashtan	↗							↗					↗												
	Msoor	↗										↗														
	Noon	↗					↘																		↗	
	Refinery	↗				↗																				
	Suhain	↗														↘										
	Tugailib	↗													↘							↘	↘			
East (Coastal)	Askar	↗										↗														
	Gaha	↗					↘																			
	Refinery	↗				↗																				
	Suhain	↗														↘										
	Season	3	1	2	3	1	2	1	2	3	4	1	2	3	4	1	2	3	4	2	3	4	1	2	3	4

and increasing in Duwaimil (East); and decreasing in autumn at Al Jasra (West).

DIN (Table 7) increased significantly in winter at four sites (Askar in East (Coastal), and Ghumais, Jabari and Msoor in East), in summer at two sites (Ghumais and Mashtan, East) and in autumn at one site (Ya'suf, West). Decreasing trends were observed at one site in spring (Bartafi, West) and two sites in autumn (Dam and Tugailib, East). Phosphate showed significant decreasing trends in different seasons at five sites. In North, decreasing trends were observed in autumn and winter at Al Jarim, and in summer at Khorfasht. In West, decreasing trends were observed in spring and autumn at Bartafi and in spring at Ya'suf (Table 7). In East (Coastal), a significant decreasing trend in phosphate was observed at one site in winter (Suhain). Silicate showed three significant trends, increasing in summer at Al Jarim (North) and spring at Gazara (East), and decreasing in autumn at Tugailib, East). For chlorophyll, significant increasing trends were observed in winter at Shtaya (Oyster Beds, as described above), in spring at Gasar (West), in summer at Ya'suf (West), Jaradah and Noon (in East), and in autumn at Umm Al Na'asan (West) and Gazara (East). A significant decreasing trend was observed in winter at Tugailib (East).

4. Discussion

The environmental data collected between 2005 and 2020 by the Supreme Council for the Environment (SCE) at various coastal and marine sites around Bahrain provides an important baseline dataset, offering a unique long-term perspective of a changing coastal system. While spatial and temporal gaps exist, the data provide a basis against which national assessment thresholds can be developed. The data have some limitations in that they don't include heavy metals or other contaminants. However, long term water quality data in the Gulf are scarce, and physico-chemical and biological data provide critical information on the condition of Gulf water quality (Devlin et al., 2015). These parameters have been used as indicators of water quality status in many other coastal systems. The breadth of literature that assesses ecological state through their use provides reassurance that they are relevant for measuring water quality status. Assessments of eutrophication, for example, use measures of nutrient inputs, nutrient concentrations, and impacts of those increased nutrients (Painting et al., 2007; Ferreira et al., 2011; Devlin et al., 2011). Nutrient inputs can lead to elevated nutrient concentrations in the marine environment, of which concentrations of dissolved inorganic nitrogen and phosphorus are key parameters (Van Beusekom, 2018; Painting et al., 2005; Greenwood et al., 2019). Elevated levels of phytoplankton biomass can be a direct effect of nutrient enrichment and are closely linked to a number of other impacts, such as reduced photic limits, toxic or nuisance algae blooms and oxygen deficiency near the seafloor (Al-Shehhi et al. 2014; Andersen et al., 2019; Devlin and Brodie, 2023).

A zonal approach was taken here to separate coastal and offshore datasets into five hydrodynamic regions. Salinity values in each of the areas agree with previously published values (ECD, 2009; Sheppard et al., 2010; Pokavanich et al., 2014), suggesting that the groupings are ecologically reasonable. Overall, monthly (Table 2) and long-term averages (Table 4) indicated better water quality in the Oyster Beds than in other areas, indicating that the sites in this area may indeed represent near-pristine conditions. This study therefore provides a first description of background conditions of turbidity, TSS, nutrients and chlorophyll and proposes candidate thresholds which could be implemented and developed further as part of future national water quality monitoring programs.

4.1. Monitoring data

The strongest seasonal patterns were observed in sea surface temperatures (14–35 °C) and concentrations of dissolved oxygen (3–12 mg l^{-1}), which were strongly influenced by temperature. Other studies describe the temperature - oxygen relationship (Quigg et al., 2013; Al-Ansari et al., 2015; Queste et al., 2018; Sankar et al., 2018) in greater detail. This suggests that oxygen concentrations may not be a useful indicator of the impact of nutrient enrichment in warm waters. This is supported by earlier work by Brodie et al. (2011) who showed that dissolved oxygen is not a good indicator of eutrophication in tropical, shallow, well mixed waters. The criteria for assessing eutrophication with dissolved oxygen as a key indicator (as described by Tett et al., 2007; Ferreira et al., 2011; Foden et al., 2011) would therefore need to be applied with caution in areas such as the Gulf. Furthermore, turbidity levels such as those reported here, and more widely in the literature (e.g. Al-Kaabi et al., 2016; Al-Shehhi et al., 2017) are likely to limit primary

Table 8
Comparison of average values for nutrients and chlorophyll from the Oyster Beds region (2014–2020, this study) with previous studies. N/A = not applicable.

	Umitaku-Maru cruises (1993-1994): Area D (Hashimoto et al 1998)		ROPME 2001 (ROPME 2012)		ROPME winter 2006 (ROPME 2012)		Oyster Beds data (2014-2020) from this study	
Parameter	µg l^{-1}	µM	µg l^{-1}	µM	µg l^{-1}	µM	µg l^{-1}	µM
Nitrate	16.81	1.2	41.07[a]	2.93	29.11[a]	2.08	13.51	0.97
Nitrite	11.21	0.8	3.06	0.22	1.4[b]	0.1	1	0.07
Ammonia	9.81	0.7	5.86	0.42	10.47[b]	0.75	5.06	0.36
Phosphate	15.49	0.5	12.35	0.4	14.67[a]/2	0.47/0.07	2.35	0.08
Silicate	112.36	4	36.32	1.28	27.13[b]	1	30.73	1.09
Chlorophyll	1	N/A	0.5-0.7	N/A	0.5-0.6[b]	N/A	0.7	N/A

(a) refers to average data obtained from highly variable datasets from waters west of the Straits of Hormuz, the sea of Oman and the Arabian Sea, biased to the higher values of the Arabian Sea. When the available maps in the report provide maps from which an approximate value can be obtained in the neighbourhood of Bahrain, this is provided.

(b) refers to values that are reasonable for Bahrain, given the variability or the information provided in the additional maps of the report.

production, for example by phytoplankton, further suggesting that it is unlikely that low oxygen levels are due to decomposition of excess organic material produced as a consequence of nutrient enrichment.

Concentrations of nutrients (with the exception of silicate) and chlorophyll were relatively low overall, despite increased risks of human impacts due to relatively long water residence times and low flushing rates in the Gulf (Al-Azri et al., 2010; Pokavanich and Alosairi, 2014). At the Oyster Beds sites, nitrite, nitrate, ammonia and phosphate concentrations were often below the limits of detection of the analytical instrument and comparable with those from oligotrophic tropical areas (e.g. McCreary et al., 2009; Harms et al., 2019; Sheehan et al., 2019), suggesting that it is realistic to consider these sites as being representative of near-pristine conditions for the purposes of water quality assessments. High levels of variability in the monitoring data due to undersampling in some months and years, reflected in higher standard errors, may need to be addressed to improve confidence in further development of water quality guidelines, especially if seasonal changes are to be considered.

Long-term averages for nutrients and chlorophyll from this study show favourable comparisons with information from historical cruises and other relatively recent, but limited, datasets (Table 8; see also Quigg et al., 2013). Al-Yamani and Naqvi (2019) compiled information on historical cruises in the period 1965–2001 and provided information on the expected ranges of concentrations of several nutrients. Hashimoto et al. (1998) sampled the Gulf in 1993 and 1994 with measurements taken close to Bahrain. To better interpret the observations, Hashimoto et al. (1998) divided the Gulf into four regions based on currents and water circulation processes with Bahrain waters being closest to area D (Hashimoto et al., 1998). The average concentrations for this area were broadly similar to background concentrations estimated in this study from Oyster Beds sites, although data were very variable (see Table 3 in Hashimoto et al., 1998).

Information from the ROPME winter cruise in 2006 and the summer cruise in 2001 (ROPME, 2012) was also compared with estimates of background conditions from this study (Table 8). Values are averages over the whole ROPME area, which is not truly representative of Bahrain waters. Nonetheless, they are broadly comparable with results from this study.

With the exception of the ROPME cruises (that also included the effect of the Gulf of Hormuz), the area D (see Table 3 in Hashimoto et al., 1998) averaged data defined on the basis of the Utaka-maru observations, provided the highest nutrient concentrations. None of the previously published datasets had enough spatial or temporal coverage to provide an indication of the variability in nutrient concentrations in the region. For example, data were relatively sparse, only available for certain years or months in particular locations, showed inconsistencies between them, and did not provide long enough time series. The most recent Oyster Beds dataset presented here provides greater consistency in that sustained observations were made at the same location over a number of years, and could be considered suitable for determining background conditions. Furthermore, they showed the lowest average concentrations of nitrate and ammonia, typically associated with human activities such as sewage discharges. Long-term and annual averages of nutrients in this study showed that the greatest variation from background conditions, as determined from the Oyster Beds area, was in the East, particularly in East (Coastal). The lowest variation was in the North area, where averages were very similar to those in the Oyster Beds.

Higher levels of ammonia observed in this study may be due to marine and terrestrial biological communities and processes. These may include high egestion and/or excretion rates by large populations of marine animals such as turtles, seabirds and dugongs, which are found in relatively high abundances (DEAP, 2009; Khamis et al., 2023). For example, a recent study at the Palmyra atoll south of Hawaii, suggests that sharks may provide an important source of nutrients to coral reefs (Williams et al., 2018). The Gulf may also accumulate nutrients for other reasons, including high levels of nitrogen-fixing bacteria (Bange et al., 2005). Significant sources of inputs are likely to be due to sewage discharges or input from industries such as the production of ammonia (and phosphate) for use in fertilisers (Abdel-Moati and Al-Ansari, 2000). Establishing improved confidence levels in the links between nutrient concentrations and human activities (such as sewage or other waste disposal and industry) is essential for determining if further management measures need to be put in place and requires monitoring of the frequency and volume of direct and indirect discharges into the marine environment.

High silicate levels reflect similar findings reported by many authors in the region (e.g. Raveendran et al., 1993; Taebi et al., 2005; ECD, 2009; Naser, 2015) and are potentially related to the increase in dust storms and changing climatic conditions (Hamza et al., 2011).

The availability of long-term data sets is useful for analysis of significant trends, making it more feasible to determine if observed changes are significant and in the direction required. For dissolved oxygen, upward or increasing trends are desirable as they potentially indicate improving ecological conditions. For all other parameters, increasing trends indicate potential impacts of environmental change or human activity on water quality. Significant increasing trends were observed only for nitrate in the Oyster Beds, East and East (Coastal). While impacts of increasing nitrate concentrations were not observed in associated trends in chlorophyll (increasing) or dissolved oxygen (decreasing), it is essential that levels continue to be monitored.

Trend analyses showed that using seasonal data may be useful in demonstrating water quality changes. Significant trends were predominantly upwards (increasing) for summer temperatures. No consistent significant trends were observed for other parameters. However, this may have been influenced by the fragmented sampling design and the limited time series and must be taken with caution. Over time, with repeated sampling, seasonal trends may become more apparent.

4.2. Development of candidate thresholds

Candidate thresholds developed from monitoring data from the Oyster Beds using a percentage deviation (as 50 % or 100 %) from background conditions follow guidelines developed elsewhere, although 50 % deviation is more commonly used (Devlin et al., 2011; Foden et al., 2011; OSPAR, 2013; HELCOM, 2015). Candidate thresholds allowing for 100 % deviation from background conditions were used here to accommodate higher levels of inter- and intra- annual variability in the data. Use of the 95th percentile was also investigated to take account of this variability. Ranges and averages in the data by hydrodynamic region support the hypothesis (Abdulla, 2019) that this region is most likely to represent near-pristine conditions, suggesting that this was a reasonable approach. Sites in North provided comparable results to those from Oyster Beds, suggesting that these data could be included in determinations of background conditions. However, higher salinities and (possibly TSS and turbidity) in North indicate that the Oyster Beds region is the most representative area of near-pristine conditions in Bahrain's waters.

In general, the 95th percentiles of the data were higher than estimates of general background conditions for oligotrophic waters or the Gulf, as described above. The 95th percentile candidate thresholds were therefore generally higher than the candidate thresholds based on 50 % and 100 % deviation from long-term averages in the Oyster Beds region. There is no precedent in any global guidelines for using 95th percentiles as thresholds, suggesting that they may be unsuitable for setting standards for assessing water quality in Bahrain and elsewhere.

4.3. Comparisons of data against candidate thresholds

Comparisons of data against the three candidate thresholds (Fig. 8) indicated the most concerns regarding water quality when the 95th percentile candidate threshold was used, and the least concerns when the 100 % candidate threshold was used. Irrespective of which candidate threshold was used, East (Coastal) showed the most water quality concerns.

The use of longer-term averages and larger reporting areas in water quality assessments can obscure important details on shorter time scales or smaller spatial scales. Nonetheless, they are valuable as a first step in assessing baseline conditions and/or water quality and can provide guidance on the prioritisation of management options. Preliminary assessments of the data presented here indicate that sites with concerns about impacts of human activity on water quality are located mostly in the broader hydrodynamic region to the East of Bahrain, particularly in the East (Coastal) region. Comparisons against the candidate thresholds in this study indicate that inputs of dissolved inorganic nitrogen (as ammonia, nitrite or nitrate) are likely to be the main concern. The source of these excess nutrients is likely to be related to sewage and industrial discharges (Bersuder et al., 2020).

It is important to note that this study used long-term averages (and 95th percentiles) of the data for the development of water quality guidelines and for comparing available data against. Insufficient data were available to develop guidelines for seasonal assessments or the use of other statistical measures (range, percentiles) or a combination of metrics into a eutrophication index, all of which are approaches also followed in other regions (e.g. Europe and the Mediterranean; see OSPAR, 2013; HELCOM, 2015). Furthermore, in our comparisons we used the entire time period of the data (2005–2020). For future assessments, a useful approach would be to carry out assessments on an annual basis (i.e. by year) or over a rolling time period (e.g. 6-year time period, see Devlin et al., 2015). These rolling assessments can then be used to supplement and add further detail to the trend assessments of the individual parameters. Additional monitoring or modelling work in the Oyster Beds region may contribute towards refining the background conditions for use in developing improved guidelines.

5. Conclusions

This study used a combination of in-situ data and international guidelines to develop marine water quality standards for Bahrain and identify the challenges of assessing a dynamic coastal environment against standards. Results indicate low levels of pollution overall. However, levels of nutrients at some sites may be a concern given the slow flushing rates of the Gulf and will inform future monitoring and assessment of environmental health in Bahrain waters. While there were gaps in monitoring frequency, the data provide an opportune data set to determine background (baseline) conditions, propose quality guidelines for future assessments, and provide preliminary assessments of water quality. The adoption and further development of water quality standards proposed here for water quality in Bahrain would facilitate assessments of environmental status for marine environmental health reports similar to those employed in other countries in the region (ROPME, 2013; Devlin et al., 2019b). Similar studies in other subtropical (e.g. Kress et al., 2019; Painting et al., 2021a) or tropical regions (e.g. Painting et al., 2021b) highlights growing concern and commitment to investigating potential water quality issues in these locations. This is a first step towards developing guidelines for Bahrain waters and proposes thresholds which can be used to identify problems at a site level or in high-risk areas. There is still much to be done to develop optimum guidelines that protect and mitigate any adverse ecological impacts. Relatively recent work in the Great Barrier Reef (Brodie et al., 2013; Brodie et al., 2017) and Chesapeake Bay (Williams et al., 2009; Williams et al., 2010) has seen the development of water quality guidelines that are explicitly related to an ecological impact, such as a chlorophyll threshold that links to a decrease in coral reef health (De'ath and Fabricius, 2010) or dry season turbidity guidelines that relate to long term seagrass growth rates (Collier et al., 2012). Future work must develop a greater understanding around the optimum range of water quality values that can protect and mitigate any adverse ecological impacts in Bahrain's marine waters. This should include information on direct and indirect inputs from land and the atmosphere (Naser, 2014). Establishing baseline environmental conditions is essential for management and conservation of Bahrain waters, which are under increasing pressure from ongoing development and global changes.

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CRediT authorship contribution statement

Suzanne Painting: Conceptualization, Writing – original draft, Writing – review & editing. **Andy J. Smith:** Project administration. **Ahmed Saeed Khamis:** Supervision, Resources, Data curation. **Khalil Hasan Abdulla:** Investigation, Data curation. **William J.F. Le Quesne:** Funding acquisition, Writing – review & editing. **Brett P. Lyons:** Funding acquisition, Writing – original draft. **Michelle J. Devlin:** Writing – original draft. **Luz Garcia:** Formal analysis, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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