Aquat. Living Resour. 2020, 33, 21
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https://doi.org/10.1051/alr/2020022

Aquatic Living Resources
Available online at:
www.alr-journal.org

Special Issue - Ecological intensification: A new paragon for sustainable aquaculture

Research Article

Spatio-temporal variation of water quality variables and hydrography in a seabream cage culture farm off the coast of Oman

Dawood Al-Yahyai[1,*], Wenresti Gallardo[2], Michel Claereboudt[2] and Gerd Bruss[2]

[1] Ministry of Agriculture Wealth, Fisheries and Water Resources, Hay Al-Wizarat, Al-Khuwair, Muscat, Sultanate of Oman
[2] Department of Marine Sciences & Fisheries, College of Agricultural & Marine Sciences, Sultan Qaboos University, Al-Khod, Sultanate of Oman

Received 21 August 2020 / Accepted 10 November 2020

Handling Editor: Jacques Slembrouck

Abstract – Mariculture cage farming in Oman is in its infancy stage. This study provides important baseline information about the initial state of mariculture in Oman and for the sustainable management of future local cage farming. Our main objective was to evaluate the spatio-temporal variations of water quality and hydrography around a gilthead seabream (*Sparus aurata*) cage farm in Quriyat (Sea of Oman). Starting in July 2018, we conducted a monitoring program over one year in which physico-chemical variables and nutrient levels were regularly measured at the farm cages and at reference sites away from the farm. Vertical flow profiles were recorded at the farm and analysed together with remotely sensed data. The results showed no significant differences among physico-chemical variables and nutrient levels between cages and reference sites. However, there were clear seasonal as well as significant short-term variations in the measurements. Winter conditions are usually homogeneous over the water column without reaching extremes. In summer we recorded surface temperatures of up to 32 °C and extended periods of hypoxia below 35 m depth. Periods of pronounced stratification were interrupted by energetic irregular flow pulses that triggered short up or down-welling events which lead to strong variations of temperature and oxygen. We did not measure a significant impact of the cage farm on the local environment. Our results rather point to the particular importance of monitoring temperature and oxygen levels. Both variables can approach threshold levels for fish farming, especially during summer. We determined the relevant characteristics of the local system and defined requirements for adequate monitoring. The findings of this study provide a timely baseline for future research on the interactions between local cage farms and the marine ecosystem and will assist in the planning and management of mariculture in Oman.

Keywords: Physico-chemical / nutrient / spatio-temporal / Oman / aquaculture

1 Introduction

In 2018, about 52% of the world's total fish production for human consumption originated from aquaculture and this is expected to reach to about 60% in 2030. The per capita consumption of fish increased from 9 kg in 1961 to 20.3 kg in 2017 (FAO, 2020). Cage culture is one of the important types of aquaculture and has developed rapidly, both in terms of technology and farming inputs (Cardia and Lovatelli, 2015).

Numerous studies have evaluated the importance of cage culture (Lester et al., 2018) and the expected effects on the environment, such as deterioration of water quality (Braaten, 2007; Azevedo et al., 2011; Abdou et al., 2017), change in sediment quality (Cromey et al., 2002; Bravo and Grant, 2018) and nutrient enrichment (Cai et al., 2016; Welch et al., 2019). The extent of the impacts from mariculture cages on the environment depends on the nature and quantity of wastes and local environmental conditions (Peran et al., 2013). Therefore, it is very important to evaluate the conditions at the selected site, such as depth, current speed and direction to determine the expected concentration and distribution of wastes from cage installation.

Holmer (2010) reviewed more than 20 research papers on offshore mariculture cage farms, all of which revealed no significant effects on the water quality. In the case of a

*Corresponding author: dawoodalyahyai@gmail.com

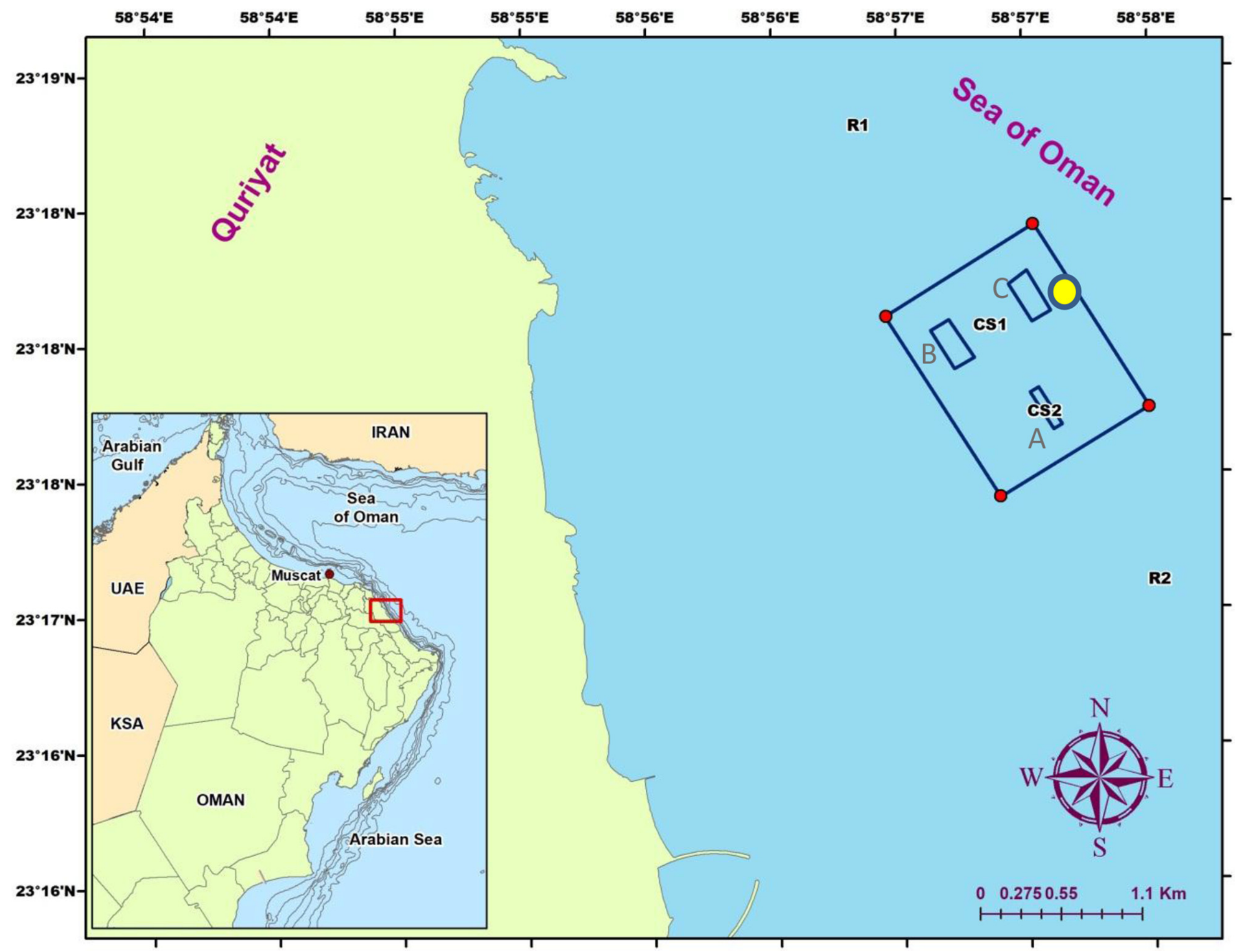

Fig. 1. Sampling locations at the cage farm site in Quriyat (ADCP device's location).

well-flushed marine site or offshore aquaculture facilities, the ecological effects could be insignificant, as currents ensure a high water exchange and more dispersion and dilution of wastes from cages (Campuzano et al., 2015), but for aquaculture facilities located inside embayment or fjords, the water quality could be affected by the aquaculture activities (Challouf et al., 2017). Price and Morris (2013) demonstrated that in the last twenty years, the significant improvement in the management practices of marine cage farms has led to reduced effects of fish farms on water quality. Moreover, Welch et al. (2019) concluded that cage farms with appropriate site and production scale have the potential to leave a relatively small nutrient footprint.

Aquaculture in Oman is a promising industry and the government has developed a national strategy plan with a main goal to produce 200 thousand tons of fish from aquaculture by year 2040 (Al-Yahyai, 2017). Mariculture cage farming is at an early stage of development, with only one cage farm currently existing in Oman. It is very important at this stage to conduct studies on the environmental situation of this farm to provide baseline information for future research and also for guidance on the future development of mariculture cage farms. Such study will help in developing regulations that protect the marine ecosystem through appropriate location of cage farms and a better understanding of the interactions between cages and environment. Therefore, this study was conducted with the aim to evaluate the spatio-temporal variations of water quality and hydrography of the cage farm.

2 Materials and methods

The study was conducted at the gilthead seabream (*Sparus aurata*) mariculture cage farm in Quriyat, South of Muscat (Fig. 1) which is operated by a private company. The farm is located 6 km offshore of Quriyat harbour, at an average depth of 60 m. The aquaculture project started in June 2017 by introducing seabream juveniles imported from Turkey. There are 32 cages in the farm divided into 3 arrays. Array A with 16 cages of 20 m (diameter) and 10 m (depth), is used for the small fish that arrived at the farm for the first time (Fig. 1). The other two arrays, B and C (each with 8 cages), contain cages of 40 m (diameter) and 15 m (depth) and are used for bigger fish until harvest. The total production in the first two years (2018, 2019) was 350 and 862 tons respectively, while the total expected production capacity of the farm is 2400 tons per annum.

Table 1. Summary of the environmental variables measured at the four sampling stations, (R1: Reference site 1; CS1: Cage site 1; CS2: Cage site 2; R2: Reference site 2) Values are mean ± SE and range.

Variables	R		CS1		CS2		R2	
	Mean ± SE*	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range
Temperature (°C)	24.85 ± 0.07	21.69–31.92	24.93 ± 0.07	21.56–31.98	24.83 ± 0.07	21.46–32.11	24.71 ± 0.07	21.40–32.21
Salinity	36.39 ± 0.01	35.92–36.92	36.39 ± 0.01	35.92–36.91	36.38 ± 0.01	35.94–36.89	36.34 ± 0.01	35.92–36.78
Dissolved Oxygen (mg L^{-1})	5.07 ± 0.06	1.83–8.95	5.09 ± 0.06	1.52–8.75	5.22 ± 0.05	1.70–8.93	4.98 ± 0.06	1.94–8.88
pH	8.27 ± 0.01	7.82–8.98	8.28 ± 0.01	7.77–9.01	8.27 ± 0.01	7.83–9.02	8.25 ± 0.01	7.82–9.05
Chlorophyll-*a* (μg L^{-1})	1.73 ± 0.05	0.06–13.78	1.92 ± 0.07	0.13–13.94	1.77 ± 0.05	0.08–11.41	1.67 ± 0.05	0.04–13.50
Turbidity (FTU)	3.32 ± 0.06	1.14–7.52	3.25 ± 0.06	1.10–7.63	3.21 ± 0.06	0.90–7.43	3.40 ± 0.07	0.69–7.47
NO_3^- (mg L^{-1})	4.89 ± 0.32	2.90–7.20	4.73 ± 0.20	3.60–6.00	4.84 ± 0.14	3.30–6.50	4.71 ± 0.27	3.30–6.30
NO_2^- (mg L^{-1})	0.012 ± 0.002	0.001–0.036	0.015 ± 0.003	0.005–0.039	0.016 ± 0.002	0.005–0.033	0.012 ± 0.002	0.003–0.030
PO_4-P (mg L^{-1})	0.34 ± 0.09	0.03–1.22	0.36 ± 0.13	0.02–1.72	0.21 ± 0.05	0.02–0.79	0.22 ± 0.04	0.02–0.48

*SE: Standard Error.

During the study period, the total production was 600 tons and only cage arrays A and B were utilized for culture activities.

Field measurements and sampling of seawater were carried out at 4 stations (Fig. 1) from July 2018 to June 2019, except for Chlorophyll-*a*, which were measured from September 2018 to June 2019. Two sampling stations were inside the fish farm, station CS1 between the cage arrays B and C and station CS2 near the group array A. Two reference sites R1 and R2 were located 1 km north and south of the cage farm and were similar to farm location in relation to water depth and currents. Physico-chemical variables including temperature (°C), salinity, pH, dissolved oxygen (mg L^{-1}), Chlorophyll-*a* (μg L^{-1}) and turbidity (FTU) were measured using CTD (Idronaut Ocean Seven 316 probe) twice a month. The measurements for these variables were vertically averaged to a resolution of 1m in the water column from surface to bottom at each station.

Water samples for nutrient analysis including nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+) and ortho phosphorus (PO_4^{-3}) were collected using a Van-Dorn sampler (WaterMark Vertical Polycarbonate Water Bottle with Case, 2.2 L) every 6 weeks. In each station, water samples were collected at 1m below the water line and 1m from the bottom and immediately transferred to clean and labeled plastic bottles (1 L), which were then stored in a cool box filled with ice. These samples were then immediately taken to the lab, which is located an hour from the farm site, for analysis using spectrophotometric methods according to HACH (2015).

Current profiles were collected at the farm site with a Sentinel ADCP from Teledyne RD Instruments operating at 600 kHz. The ADCP was fixed to a horizontal cage mooring at the south eastern corner of the cage array C (Fig. 1) at a depth of 9 m below the surface. The device was installed to face downwards, thus recording the velocity profile, approximately between the bottom of the fish cages and around 1–2 m above the sea floor. The ADCP was operated between 8. November 2018 and 15 May 2019 interrupted by a maintenance break between 10 January and 12 February 2019. For this study the raw ADCP data sampled every 30 seconds was low pass filtered and interpolated to a temporal resolution of one hour.

Sea level data for the years 2018 and 2019 were obtained from the tide gauge at port Quriyat through the sea level station monitoring facility of the Intergovernmental Oceanographic Commission of UNESCO (UNESCO/IOC, 2020). Tidal analysis was performed on the data using the u-tide Matlab toolbox (Codiga, 2011) to extract characteristic properties of the local sea level variation.

Satellite-derived level 4 products were obtained through the Ocean Products Portal of the Copernicus-Marine environment monitoring service (http://marine.copernicus.eu/services-portfolio/access-to-products/). Data for wind stems from the CERSAT project, sea surface temperature (SST) was obtained from OSTIA and geostrophic flow from DUACS. Extensive descriptions of these datasets can be found through the above-mentioned data portal. CERSAT and DUACS products were retrieved as time series for the sampling period from pixels closest to the fish farm; daily SST was obtained for the entire Sea of Oman for 13 yrs, from 1 January 2007 to 31 December 2019.

Two-way ANOVA tests were used to determine the significant differences in environmental variables at the different stations using R (R Core Team, 2019). The factors for the analysis were locations (fish farm stations vs control site stations) and time. Pearson correlation coefficient tests were performed to evaluate the strength of relationships between the environmental water variables. For all tests, the null-hypothesis was rejected if the p-value was >0.05.

3 Results

Table 1 shows the mean, standard errors (±SE) and range of all environmental variables measured at the four stations.

Temperature for all stations ranged from 21.40 to 32.21 °C (Tab. 1). These highest and lowest records were in reference station R2 in June 2019 at the sea surface, and in April 2018 at depth of 50 m, respectively. There were no significant differences ($p = 0.163$) in seawater temperature between the four stations. The temperature showed a clear annual variation (Figs. 2 and 3) with four characteristic seasonal conditions: an

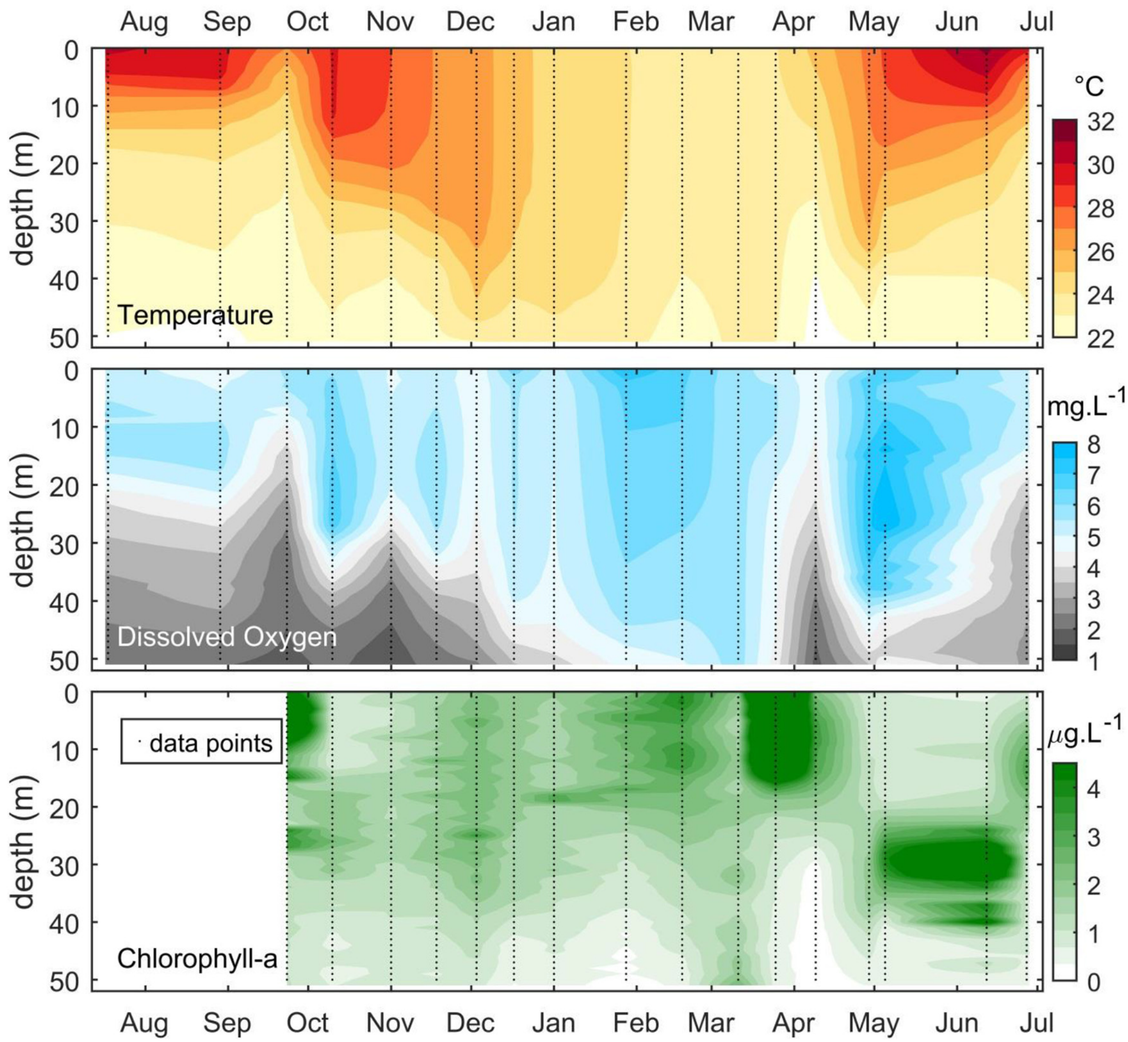

Fig. 2. Vertical distribution of temperature, dissolved oxygen and Chlorophyll-*a* at the farm (average all stations) between July 2018 and July 2019.

early summer-high in June/July when SST reached 32 °C followed by a decrease in surface temperatures during the period of the SW monsoon between August and September. After the summer monsoon, in October, a second, lower, summer-high appeared, after which, the surface temperature dropped to the winter-low of 23 °C in March. Starting in April the temperatures at the surface rose steeply to the first summer peak in little over two months. Surface temperatures underwent high variability between April and October, compared to the steady temperature decline after October.

Looking at the vertical temperature profiles (Fig. 2), the seasonal cycle mainly manifests in the vertical migration of the thermocline. A generally shallow and steep thermocline in summer migrated downwards in winter. The decrease in surface temperatures was accompanied by an increase of temperatures at 50 m depth. In February and March, the temperature at the farm site was nearly uniform over the entire water column. Figure 3 compares satellite data for SST to the CTD measurements at 1m depth and the ADCP records at 9 m depth. CTD surface temperatures and satellite SST matched within ±1 °C with three CTD records below the satellite data. While the ADCP data followed the SST and CTD temperature at 1 m depth between November and March, it revealed periods of high temporal variability of temperature at 9 m during April and May.

The analysis of the 13 yr dataset of remotely sensed surface temperature along the northern Oman coast revealed an increase of the overall mean SST from 26.7 °C at Ras Al Hadd, 27.9 °C at Muscat, to the maximum of 28.3 °C at Sohar. There is only a small spatial variation (±0.5 °C) around the average winter-low of 23.3 °C. Average summer peak temperatures increase from 29.0 °C at Ras Al Hadd to 31.5 in Muscat and 33.0 °C in the northwestern Sea of Oman.

The highest record of pH was 9.05 in reference station R2, while the lowest was 7.77 in cage station CS1 (Tab. 1). While there was a significant difference between cage station CS1 and reference station R2 for pH ($p = 0.0179$) and salinity ($p = 0.0319$), there was no significant difference between this cage site and reference station R1 for pH ($p = 0.399$) and salinity ($p = 0.531$). There was also no significant difference

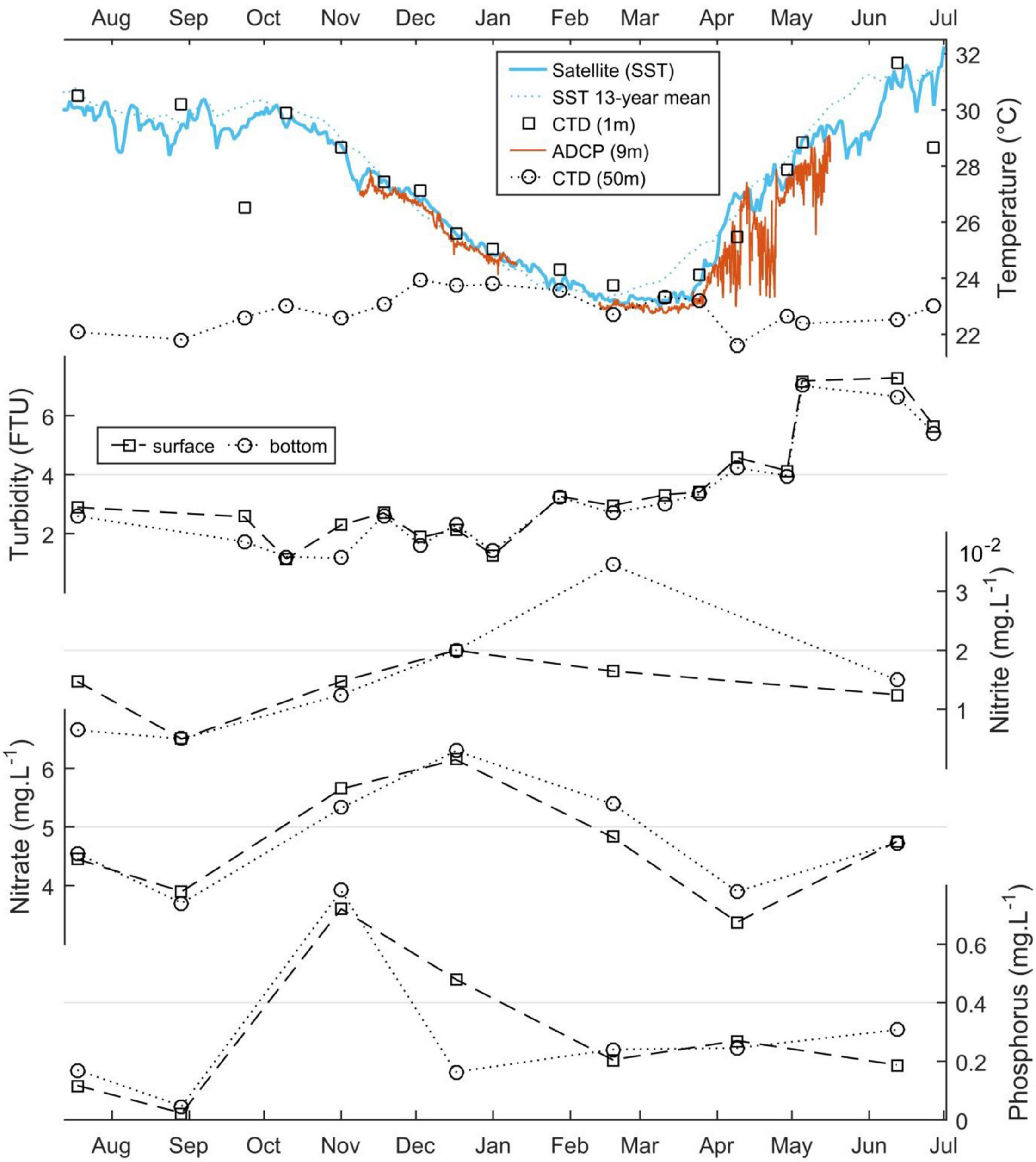

Fig. 3. Sea temperature at different depths and from different sources, turbidity, nitrate, nitrite and phosphorus at the farm (CTD and nutrient data is averaged over all stations) between July 2018 and July 2019.

between cage site CS2 and the two reference sites R1 and R2 for pH ($p = 0.056$) and salinity ($p = 0.119$).

The highest record of dissolved oxygen levels was 8.95 mg L^{-1} in reference station R1 in January 2019, at the sea surface, while the lowest was 1.52 mg L^{-1} in cage station CS1 in September 2018, at a depth of 50 m (Tab. 1). There were no significant differences ($p = 0.288$) in these levels between the four stations. However, there was seasonal variation (Fig. 2). There was a long period of hypoxia (DO <2–3 mg L^{-1}) from March to the end of December. During this period, the levels decreased to a minimum of 1.52 mg L^{-1} at a depth of 50 m in cage site CS1. At both cage sites, CS1 and CS2, the DO ranged from 1 to 3 mg L^{-1} from the bottom (50 m) up to 35 m. From January to the end of March, there was homogeneity in the levels across the water column from surface to bottom, where DO levels were above 4 mg L^{-1} in all stations (Fig. 2).

The highest Chlorophyll-*a* (Chl-*a*) level recorded was 13.94 µg L^{-1} in station CS1 in March 2019, at the sea surface, while the lowest was 0.04 µg L^{-1} in reference station R2 in January 2019 at a depth of 46 m (Tab. 1). There were no significant differences ($p = 0.123$) found between the four stations, however seasonal variation was observed (Fig. 2). Chl-*a* distribution in the water column was different in autumn and spring, but all stations showed similar trends in summer and winter. These differences in autumn and spring occurred from the surface down to the depth of 20 m, below which the concentration tended to be homogeneous for all sites.

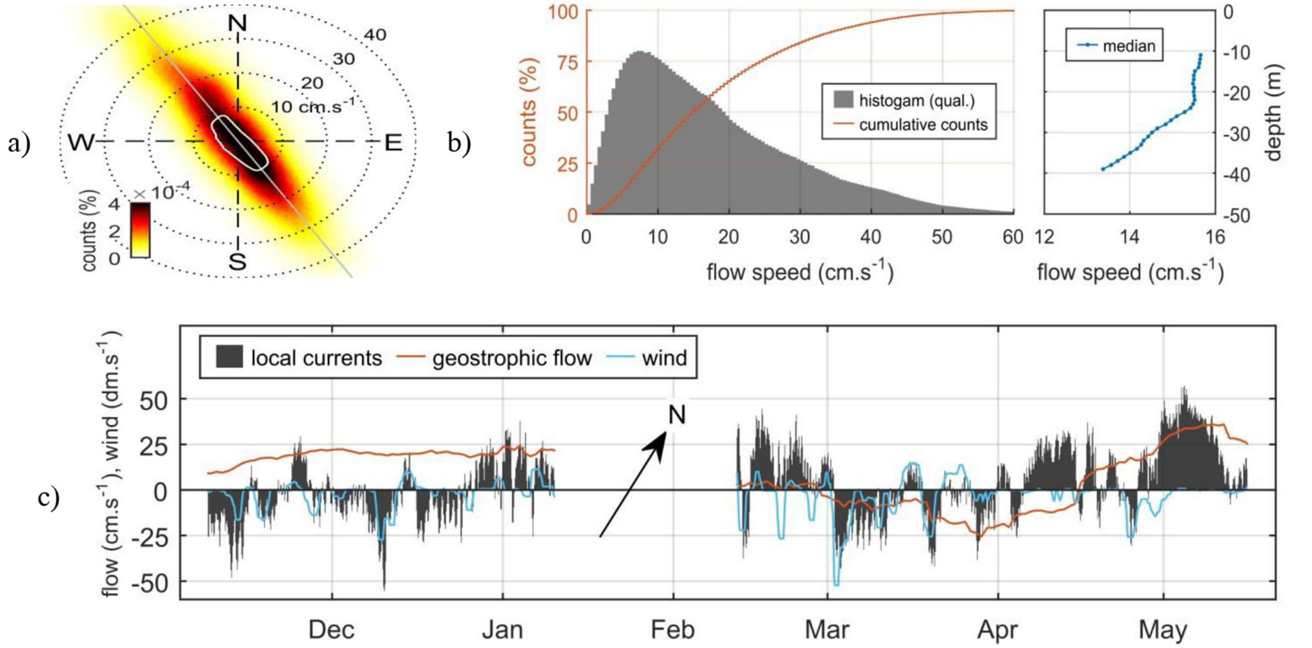

Fig. 4. Flow conditions at the farm site between November2018 to May2019: (a) Directional histogram of currents with principal axis. (b) Qualitative histogram, cumulative probability and vertical median of the recorded flow speed. (c) Coast parallel components of depth-averaged ADCP currents, offshore geostrophic flow and wind.

The highest turbidity recorded was 7.63 FTU in station CS1 in June 2019, at the sea surface, while the lowest was 0.69 FTU in reference station R2 in October 2018, at a depth of 9 m (Tab. 1). There were no significant differences ($p = 0.293$) in turbidity between the four stations, however seasonal variation was observed. For both surface and bottom levels, turbidity showed a general trend of increase during the study period (Fig. 3).

The lowest level of nitrate was 2.90 mg L^{-1} in reference station R1 in April 2019, at the surface, while the highest level of 7.20 mg L^{-1} was also in the same station in December 2018, at the bottom (Tab. 1). There were no significant differences ($p = 0.694$) found in nitrate between the four stations, however seasonal variation was observed (Fig. 3). At each station, there were no significant differences between nitrate levels at surface and at bottom samples ($p = 0.217$). The highest average readings of nitrate for surface and bottom were recorded in December, at 6.15 mg L^{-1} and 6.30 mg L^{-1} respectively (Fig. 3).

The lowest nitrite level was 0.001 mg L^{-1} in reference station R1 in February 2019, at the surface, while the highest level of 0.039 mg L^{-1} was in the cage station CS1 in February 2019, at the bottom (Tab. 1). There were significant differences ($p = 0.043$) in bottom nitrite levels between cage station CS1 and reference stations R1 and R2. Nitrite levels showed seasonal variation (Fig. 3). At each station, there were no significant differences between nitrite levels at surface and bottom ($p = 0.223$). Higher readings were obtained in December 2018 and February 2019, with no detection of nitrite in April 2019.

The lowest phosphorus record was 0.02 mg L^{-1} in cage stations CS1 and CS2, registered in August 2018 at the surface, for both locations, while the highest record was 1.72 mg L^{-1} in cage station CS1, measured in November 2018 at the surface (Tab. 1). There were no significant differences ($p = 0.554$) in phosphorus between the four stations, although seasonal variation was observed. At each station, there were no significant differences between phosphorus levels at surface and bottom ($p = 0.376$). The highest levels of phosphorus were in November, for both surface and bottom (Fig. 3).

Ammonia was not detected in any sample from stations at the Minimum Detection Limit (MDL) of 0.01 mg L^{-1}, except in December 2018, where the average surface and bottom levels were 0.09 mg L^{-1} for all stations. The minimum level recorded in December was 0.06 mg L^{-1} at the surface in cage station CS2, while the highest level was 0.12 mg L^{-1} at the bottom in the same station.

From the sea level data of the tide gauge at the port in Quriyat we found the local tidal range to be around 0.5 m at neap and 3 m at spring tide. Figure 4 shows flow conditions and its statistics at the farm site between November 2018 and May 2019. The white contour in Figure 4a includes 95% of the tidal currents. Tidal currents always remain below 10 cm s^{-1} and account for only about 30% of the flow variability at super inertial frequencies.

The principal axis of the total flow (grey line in Fig. 4a) is oriented roughly parallel to the coastline along 330°–150°. Flow along this axis explains 97% of the total variability, with approximately even distribution between the two main directions during the recorded periods. The histogram of the flow magnitude in Figure 4b reveals a right-skewed distribution with the mode around 7.5 cm.s^{-1}. During around 70% of the recorded period the flow speed was above 10 cm/s and 5% of the time the local current exceeded 40 cm.s^{-1}. The median of the flow speed decreased from 15.7 $cm.s^{-1}$ at 10 m to 12.0 $cm.s^{-1}$ at 45 m depth, with the depth integrated median around 14.0 $cm.s^{-1}$.

The strongest currents of 63 cm/s directed towards north-west were recorded on 4th May 2019 at around 20 m depth. Panel c of Figure 4 shows the time series of the depth averaged flow at the farm site, superimposed to nearby geostrophic flow and regional wind from satellite data. The flow at the farm appears in the form of pulses that alternate between the main coast parallel directions with variable intensity and duration. The most intense pulse appears over a period of around 10 days in early May, with strong north-westerly currents. Regional wind is correlated to the local flow with $r = 0.4$; while strong geostrophic flow 20 km offshore of the farm site coincides with the intense local pulse in early May (Fig. 4c).

Pearson correlation analysis showed that temperature was positively correlated with dissolved oxygen ($r = 0.516$, $p = 2.2\ 10^{-16}$). The pH was positively correlated with turbidity ($r = 0.663$, $p = 2.2\ 10^{-16}$), but negatively correlated with Nitrate ($r = -0.683$, $p = 6.8\ 10^{-09}$).

4 Discussion

The annual Average Surface Sea Temperature SST for the sampled year (27.4 °C) was slightly below the average of the preceding 13 yrs (27.8 °C). The main reason for this is the unusual extension of cold conditions into March 2019 and the two weeks of reduced SST in late May 2019 (Fig. 3). Except for these two periods the conditions of the study period represent an average year, fairly well.

The seasonal variation of the surface water temperature reflects the solar radiation cycle and the influence of the Arabian Sea monsoon. Highest surface temperatures of 31–32 °C occur in late June, approximately one month after the solar radiation maximum while lowest sea temperatures of around 23 °C appear in February and March and lag two to three months behind the local solar radiation minimum (Al-Hinai and Al-Alawi, 1995). This annual cycle of the SST is further influenced by the monsoon. From July to October the south-west monsoon over the Arabian Sea leads to a cooling of hot summer conditions in the southern Sea of Oman (Al-Hashmi et al., 2019a). Average sea surface temperatures are reduced, while their short-term variability increases during this period. The main drivers are an irregular northward advection of upwelled water from the Arabian Sea and local up/down welling events following strong local wind or intense eddy activity (Pous et al., 2004; L'Hegaret et al., 2013).

The vertical temperature stratification also varies markedly with the seasons. Distinct seasonal stratification patterns have been reported for several locations on the northern Omani shelf (Al-Hashmi et al., 2010, 2019a; Claereboudt, 2018). At the farm, sea surface temperatures start to rise quickly at the beginning of March, leading to the development of a shallow thermocline. In the presence of a strong and shallow thermocline, events of up/down welling result in high temperature fluctuations of up to 6 °C/day in the upper water column. From November to March the thermocline remains below the cage level. Despite similar circulation intensity, as in summer, vertical homogeneity during winter prevents rapid changes of temperature.

The temperatures measured at cage level (23–32 °C) were within the temperature tolerances for cultured gilthead seabream (*Sparus aurata*), which are 18–34 °C (Okte, 2002; EFSA, 2008; FAO, 2005). Balbuena-Pecino et al. (2019) showed that an increase in water temperature from 19 to 24 °C and especially to 28 °C during the rearing of gilthead seabream juveniles (50 g), can lead to unfavourable growth conditions for the musculoskeletal system. Summer temperatures at the Quriyat farm appear at the upper end of the reported tolerances and can strongly fluctuate. Therefore, more detailed studies and monitoring of the thermal effects on the locally cultured seabream are needed.

Quriyat is located ∼120 km north-west of the opening to the Arabian Sea at Ras Al Hadd. Despite being well inside the Sea of Oman, the conditions reported here for Quriyat are not fully representative for the entire northern Omani coast. The annual mean SST increases from 26.7 °C at Ras Al Hadd, 27.9 °C at Muscat, to 28.3 °C at Sohar. Kwarteng and Mozumder (2016) report an average of 27.5 °C for the Strait of Hormuz. While there are only small spatial variations (±0.5 °C) in the average winter temperature of 23.3 °C, highest summer temperatures increase from 29 °C at Ras Al-Hadd, to 31.5 in Muscat and 33 °C in the north-western Sea of Oman. Around Muscat there is a transition between a wide shelf with shallow slopes towards Sohar and a narrow and steep continental shelf towards Ras Al-Hadd in the south east. This generally results in more dynamic conditions, similar to the ones reported here, east of Muscat. West of Muscat, the conditions appear calmer and more stable, with a strong and shallow thermocline (Chitrakar et al., 2018; Claereboudt, 2018; Al-Hashmi et al., 2019a) and generally higher surface temperatures.

The comparison of the different temperature records (CTD, ADCP and satellite SST, Fig. 3) allows us to relate sampling resolution to temporal variability and to estimate the extent to which SST can be used to infer temperatures at lower levels. The satellite data from OSTIA is averaged over 4 km pixels and at daily intervals. It represents the foundation temperature at the base of the diurnal warming layer. Except for two records, the differences between surface temperature from CTD and satellite SST lie within ±1 °C and give an indication of the general diurnal (and spatial) variability of local SST. When daily SST averages fall below the instantaneous (daytime) CTD measurements, stable conditions with a shallow thermocline and a pronounced diurnal warming can be inferred. The CTD records of late August 2018 and early June 2019 illustrate the connection between a shallow thermocline and high CTD surface temperatures. Overestimation of instantaneous CTD temperatures by satellite SST points to sub-diurnal vertical mixing, possibly driven by the locally frequent, daytime sea-breeze. Examples are the records of September 2018, April and late June 2019, when the CTD temperature at 1m fell well below the satellite SST. High frequency fluctuations of the ADCP temperature during April confirm the link to increased dynamic mixing. The approximately monthly CTD sampling captured the annual cycle, while the frequent short-term variations of the pulse driven system were not resolved. Considering vertical stratification, the CTD profiles show that before

December and after April, SST can deviate significantly from temperature at the lower cage levels (10–20 m) and is thus not well suited for operational monitoring.

The current farming activities in the cage farm have no effects on the dissolved oxygen levels in the marine environment. The results showed no significant differences between cage and reference stations. This is consistent with the findings of Sara (2007) who conducted a meta-analysis of 30 peer-reviewed articles and found that there is no effect on DO level from farm operations. Yabanli and Egemen (2009) also found similar results in the Aegean Sea. Abo and Yokayama (2007) estimate the minimum critical value of DO required for sustainable aquaculture production to be 4 mg L^{-1}. The DO levels that we measured at the farm sites CS1 and CS2, down to the maximum depth of the cages (15 m) were always above this threshold.

There is a strong positive correlation between dissolved oxygen and temperature. The Sea of Oman and the Arabian Sea have a very low oxygen content and the minimum oxygen zone can be as shallow as 60 m (Piontkovski and Al-Oufi, 2015; Queste et al., 2018). In summer and fall, a strong stratification dramatically decreases the exchange of water across the thermocline. Notable differences in dissolved oxygen concentrations appear in summer between surface and bottom water layers, with average concentrations of 5.7 and 2.6 mg L^{-1} respectively. Local upwelling events during summer bring the thermocline near to the surface, allowing some mixing between warm, oxygenated surface water and cool, anoxic deep water leading to an overall decrease in both temperature and dissolved oxygen. After such mini-mixing events, the input of nutrients associated with the upwelling triggers primary production in shallow water, which may further decrease the DO content. Once the phytoplankton dies, it sinks and its decomposition will decrease the DO in the deeper water as observed from May to November 2018 (Fig. 2). In winter, the lower surface temperature decreases stratification and facilitates downward mixing of oxygenated surface water. This leads to less variation in dissolved oxygen concentration between surface and bottom water layers, with average concentrations of 6.2 and 4.1 mg L^{-1} respectively. Similar variations of dissolved oxygen were obtained in other studies in the Sea of Oman (Chitrakar et al., 2018).

Diaz and Breitburg (2009) defined hypoxia as the oxygen level below 2–3 mg L^{-1} for marine water, with different threshold levels of hypoxia based on cultured species. Based on this definition, our study showed that there were long periods of hypoxia (before December 2018 and after June 2019), up to a depth of 35 m at the farm cages. In September, this level of hypoxia reached to a depth of 12 m in cage station CS2. Therefore, our data show the importance of continuous monitoring of the vertical DO profile near the aquaculture cages, to evaluate and assess the fluctuations in the hypoxic layers. This will be beneficial not only during the initial phases of the project but also for the marine ecosystem as an expansion of the farm may affect the oxygen levels. At an operational level, it is very important for the cage farm to develop a contingency plan to deal with this risk of shallow.

Despite the high concentrations of chlorophyll-*a* in certain periods, at certain depths, the general levels of concentrations during the study period were between 0.04 and 3 μg L^{-1}. These periods were in September 2018 at surface depths of 1–12 m except for station CS1 which occurred at middle depths of 15–27 m, end of March 2019 at depths around 1–17 m and mid of June 2019 at depths around 24–40 m.

These concentrations were within the range found in other studies in the Sea of Oman (Al-Hashmi et al., 2010; Kwarteng and Mozumder, 2016). These high concentrations are likely due to the natural phytoplankton activities. This study found no effects from current mariculture cage farm activities on the concentration of chlorophyll-*a,* as there were no significant differences in its levels between the cage and control stations. Similar observations for cage culture of gilthead seabream in particular and other marine species in general were obtained from studies in Turkey (Basaran et al., 2010), Tunisia (Challouf et al., 2017), Mauritius (Sadally et al., 2014) and Italy (Vezzulli et al., 2008).

In general, the effect of marine cages on turbidity levels has not been given a high priority in the literature, compared to freshwater aquaculture (Sara, 2007; Price et al., 2015). The cage site with high flushing rates has low turbidity levels due to dispersion of wastes from the cages (Sara, 2007). Our study showed no significant difference between cage and reference stations for turbidity levels.

Despite a significant difference ($p = 0.0284$) in bottom nitrite levels between cage station CS1 and reference stations R1 and R2, the post-hoc analysis revealed that the difference was not highly significant ($p = 0.043$). The higher nitrite levels we observed in December and February were possibly due to water column mixing in this period of low density stratification. A previous study on the cage site did not detect nitrite in the water samples (Blue Water, 2016). The values of nitrites in our study were well below some international standards for nitrites (Philminaq, 2008; OATA, 2008; Friend of the Sea, 2014). However, it is important to monitor nitrite levels on a regular basis to determine the seasonal fluctuations and the future trends of its levels.

Ammonia was not detected in any sample from any stations, except during one sampling mission in December 2018. The highest level of ammonia during December was 0.12 mg L^{-1}. This level was lower than the Australian and New Zealand standard of <1.0 mg L^{-1} (ANZECC, 2000) and also lower than the standard set by Friend of the Sea (2014) for sustainable marine aquaculture, which should be less than 1 mg L^{-1}.

Average nitrate concentration in both surface and bottom depths follow similar trends. Increased nitrate levels were likely to follow the shallowing thermocline depth during upwelling events. The nitrate concentrations increased during winter season compared to other seasons. However, this seasonal variation is minimal. This study showed no significant differences between cages and reference locations and this is similar to the results of a study conducted in the eastern Aegean Sea in Turkey (Basaran et al., 2010). The nitrate levels in our study were lower than the international standards (ANZECC, 2000; Friend of the Sea, 2014). A previous study on the site before cage installation indicated the slight increased trend in the nitrate levels (Blue Water, 2016). Our results were higher than those measured by Blue Waters (2016). Therefore, it is important to periodically monitor the nitrate levels in the farm site to evaluate the seasonal and future trends.

As this cage farm has future plans to expand the production to reach 3000 tons, the continuous monitoring of the output trend of dissolved nitrogen will be important for the ecological sustainability of the farm.

Phosphorus levels recorded in our study were higher than those recorded by Blue Waters (2016) on the cage site. Several studies have revealed the relative enrichment of phosphorus in the Sea of Oman, which can be related to the fact that nitrogen is the limiting factor for primary production (Al-Hashmi et al., 2019b). Phosphorus levels in the range of 0.015–0.11 $mg\,L^{-1}$ were obtained at a site of about 32 km north of the current study area, by Al-Hashmi et al. (2019b). The phosphorus levels in the current study were almost higher than international standards stated in Friend of the Sea (2014). This study showed no significant differences in phosphorus levels between cage and reference stations and this finding comparable with a study on seabream in Turkey (Neofitou and Klaoudatos, 2008). Based on the current study and the previous studies conducted on the Sea of Oman, there has been a clear, increasing trend in the level of phosphorus over the years and thus it is important to monitor it at regular intervals, to determine the seasonal fluctuations and the future trends of its levels.

The flow at the farm site is strongly aligned along its principal axis, which corresponds to the orientation of the local coastline (Fig. 4a). Flow along this axis explains 97% of the total variance. This means that farm waste dispersal towards the shoreline can be expected to be low. Despite a tidal range of up to 3 m at the port in Quriyat, the local tidal currents at the farm are small. The water depth of ~60 m at the farm site and the steep and narrow shelf do not induce strong tidal flow. Local flow above 10 $cm\,s^{-1}$ appears as aperiodic pulses. Flow pulses are observed to occur in both long-shore directions in approximately equal frequency.

The averaged flow, recorded at depth at the farm generally follows the patterns of the regional wind (Fig. 4c). However, not all wind events are reflected in the flow and not all flow pulses coincide with increased wind. Another important regional oceanic driver are mesoscale eddies that appear frequently in the Sea of Oman (L'Hégaret et al., 2013, 2015). In Figure 4c geostrophic offshore circulation is only sporadically related to local flow but can trigger strong pulses if intense eddies approach the shelf. In early May 2019, an intense anticyclone developed and moved southwards in the eastern Sea of Oman, driving strong currents at the farm for more than a week without the presence of considerable wind.

Looking at the vertical flow profile in Figure 4b, between 20 and 30 m, the time averaged flow speed starts to deviate (decrease) from the uniform distribution above. This indicates a depth range of enhanced vertical flow shear below the fish cages. The flow shear could suggest the influence of a thermocline, during the period of the flow recordings; however, no pronounced thermocline was present. Another factor that can influence the vertical flow profile is the drag of the cages onto the flow. An undisturbed flow profile might have higher median velocities in the upper layers. Instantaneous flow profiles during conditions of intense flow show vertical variation, depending on the driving mechanism. Wind induced flow is stronger in the upper layers, while high currents driven by geostrophic circulation can appear isolated in lower layers. During seasons in which a pronounced thermal stratification can develop, flow pulses are related to temperature fluctuations in the upper layers. The main mechanisms by which flow affects local temperatures are: horizontal advection, up/downwelling and vertical mixing.

The Norwegian Standard NS-9415 (NAS, 2009) sets criteria to ensure structural integrity of mariculture farms and to prevent fish from escaping. Five classes are defined based on flow speed ranging from 'little' to 'extreme exposure'. According to this classification, the median of the flow recorded at the Quriyat farm ranged in the 'little exposure' class. Around 25% of the time there was 'moderate exposure' and the conditions during intense flow pulses (~3%) constituted 'substantial exposure'. While more conservative classifications (higher exposure at low flow speed) are discussed when fish welfare is considered (Jónsdóttir et al., 2019), stronger flow is desirable for farm waste dispersal and nutrient assimilation (Gentry et al., 2017).

The pulse-character, together with the high vertical and temporal variability of the local flow, requires detailed analysis to determine reliable estimates of the dispersal and fate of particulate and liquid wastes from the farm. Such analysis is beyond the scope of this paper and will be conducted in a separate study. The local flow patterns as described here, based on the records taken at the farm site, can only be considered representative for the northern part of the Sur-Muttrah coastline. Conditions in other parts of the Oman coastline differ significantly in their dynamics (Pous et al., 2004).

5 Conclusion

The results of this study showed that the mariculture cage farm at Quriyat had no significant effect on the local marine ecosystem. The physico-chemical variables and nutrient levels that we measured at the fish cages did not differ significantly from the values at reference sites. The continuation of regular water quality monitoring around the farm is still essential, to determine any changes or future trends in these variables.

During calm summer conditions we measured high surface temperatures with a strong thermocline and low oxygen levels at deeper depths. Both parameters can approach critical thresholds for marine aquaculture, which further indicates the demand for continuous monitoring. The monitoring can be adapted to the seasonal cycle. During winter, when strong vertical mixing, low temperatures and higher oxygen levels are present, monitoring intervals can be longer (weekly) and data collection can partly be based on readily available satellite products. During stratified summer conditions, surface data is not a good indicator for temperature at lower levels and short-term events of local upwelling can furthermore reduce oxygen levels. Vertical measurements at higher temporal resolution (daily) are thus required during this season.

At this early stage of mariculture cage farms development in Oman, this study forms a baseline for future studies on the interactions between cage farms and the marine environment. This will assist in the environmental management process aiming to minimize the effects of farm activities on the surrounding marine ecosystem.

Acknowledgments. The authors wish to thank Blue Waters Co. for their support and access to the farming sites during sampling campaigns. Special thanks to Mr. Salim Al-Khusaibi from the Department of Marine Science and Fisheries at Sultan

Qaboos University for his kind and invaluable assistance during the field missions.

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Cite this article as: Al-Yahyai D, Gallardo W, Claereboudt M, Bruss G. 2020. Spatio-temporal variation of water quality variables and hydrography in a seabream cage culture farm off the coast of Oman. *Aquat. Living Resour.* 33: 21