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Wind and shipping influences on sea currents around an inshore fish farm in a heavily contested Mediterranean embayment

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A B S T R A C T

Marine aquaculture expansion will continue to be challenged by a lack of space in areas of the marine domain that can support aquaculture, due to competition from other maritime activities vying for the same spaces. This research attempts to characterise those natural and anthropogenic forces that influence and drive sea currents measured over a 16-month period around a nearshore fish farm located within a busy multiple-use bay in the central Mediterranean Sea. Evidence from a concomitant two-year-long meteorological dataset reveals the occurrence of variable winds that result in a dominant and perpetual forcing on near-surface current magnitude and direction. The correlation coefficient between wind and sea currents decreases with increasing depth and hourly time lag. Moreover, the observed water level variations were more related to meteorological forcing factors than to tidal influences recorded at the mouth of the bay. However, intermittently observed water current values could not be exclusively explained by atmospheric forcing variables when the relationship between *in-situ* measurements and sea current values predicted by the hydrodynamic-wave model (Marine Forecasting System) was analysed. Consequently, this lack of correlation spurred further analysis, which revealed that relevant water current disturbances, particularly in near-surface sea currents, corresponded to 131 different Automatic Identification System (AIS) records of vessels. These vessels included bunkering barges, pilot boats and dredging vessels operating and navigating within a 650 m radius from the fish farm and during a 10-min window. This study thus provides evidence for natural and anthropogenically-derived influences on local fish farm-scale hydrodynamics that have important implications for the effective and sustainable development of aquaculture within a marine spatial context, especially in congested, multi-use environments.

1. Introduction

Around the world, coastal bays and inlets are multiple use areas that cater for different activities. For decades, sheltered inshore areas have provided suitable environmental conditions for marine aquaculture, particularly for juvenile production. However, lack of space and competition from other coastal activities challenges the development of marine aquaculture (Sanchez-Jerez et al., 2016; Cavallo et al., 2020; Galparsoro et al., 2020) especially where it exists in multi-used bays or port and harbour areas. Recently, aquaculture and other coastal activities are increasingly undertaken within the wider context of marine spatial planning (MSP) (Sanchez-Jerez et al., 2016). Indeed, Deidun et al. (2011) advocated for scientific guidance to address knowledge gaps that could otherwise be a barrier for effective MSP. For this reason, spatial development and management of coastal activities should be based on evidence-based decision-making (Pınarbaşı et al., 2017). The development of marine aquaculture, especially where space is limited and competition is significant, requires a thorough understanding of the natural and anthropogenic factors that affect it.

There is increasing reliance on hydrodynamic models in planning and management of marine space. Planning measures and policies for spatial development and management in coastal waters rely on sound understanding of the hydrodynamics and the forces that drive them in these coastal areas (Montaño-Ley et al., 2007). Still, research on the forcing factors and the processes that influence and drive water movement in many of these coastal environments is limited. In the Mediterranean region, model simulations have revealed wind-dominant influences on water

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movement over tidal effects in sheltered coastal areas (Ferrarin and Umgiesser, 2005; De Marchis et al., 2014; Grifoll et al., 2014; Balsells et al., 2020). However, the hydrodynamics of complex coastal areas may not necessarily be simulated accurately through simplistic or idealised scenarios (Grifoll et al., 2009; De Marchis et al., 2014; Grifoll et al., 2014). For instance, port and harbour hydrodynamics can also be influenced by event-specific factors like anthropogenic forcing. When these are not accounted for, simulations fail to provide a detailed hydrographic representation around fish farm cages. In these situations, decision-support tools may have limited applicability. For marine aquaculture, a detailed description of hydrography can aid decision-support tools in providing a more accurate assessment of waste dispersion, farm production, hydrodynamic effects of fish farm infrastructure and environmental impact in these coastal areas.

Anthropogenic activity adds qualitatively distinct disturbances to natural forcing that can induce different effects and implications for these coastal systems (Soomere, 2007; Scarpa et al., 2019). Notably, ship-generated water movement has different characteristics to wind-induced hydrodynamics with sediment resuspension altered by vessels by as much as one order of magnitude greater within seconds (Soomere, 2007; Rapaglia et al., 2011). These abrupt ship-related hydrodynamic disturbances can occur more frequently and have greater effect on the surrounding aquatic environment, more so when combined with wind effects (Gabel et al., 2017). The rapid increase in shipping traffic will continue to put pressure on the environment (Rapaglia et al., 2011; Fleit et al., 2016; Gabel et al., 2017) and coastal users like marine aquaculture (Pearson et al., 2016; Gabel et al., 2017).

Research has described different challenges in human-dominated seascapes with the rapid development of maritime activity across the world (Fernández et al., 2016; Pearson et al., 2016). For instance, intermittent dredging not only has hydrological impact but can also cause resuspension and dispersion of contaminants from sediment (Airoldi et al., 2016). Water movement can facilitate the resuspension and transport of sediments, and affect fish behaviour and physiology, especially if exposed to contaminated sediments associated with industrial coastal areas, ports and shipping. Flow around fish cages disperses waste that is generated from marine aquaculture and supplies oxygenated waters that is essential for fish welfare and production in marine aquaculture (Klebert et al., 2013). Similarly, shellfish production is strongly influenced by water movement for the supply of food and oxygen (Dame and Kenneth, 2011; Campbell and Hall, 2019). Therefore, water movement is key in marine aquaculture and requires thorough understanding in planning, managing and developing the sector.

In Malta, coastal space is a serious limitation for coastal aquaculture where already 22.9% of the coastline is used for fish aquaculture, in contrast with less than 3% in other European countries (Hofherr et al., 2015). In the Mediterranean region, marine fish farms sited in multi-used bays and port areas are not unusual, with examples from Israel, Mallorca, Sardinia and Turkey, and shellfish farming in Sardinia and Andalusia. This observational study describes water current variability around an inshore fish farm situated in a busy multiple use bay and port area in the Mediterranean Sea. This research investigates the relationship between water currents and the natural and anthropogenic forces, wind and ship traffic, and then describes the implications for other coastal activities, particularly marine aquaculture. This work aims to contribute towards new solutions for the sustainable development of aquaculture, especially where it is challenged by coastal space and co-existing maritime industries.

2. Materials and methods

2.1. Study site

The Marsaxlokk Bay is at 35°49′32.23″N in longitude and 14°32′35.46″E in latitude, located in the southeast of the Maltese archipelago, at the centre of the Mediterranean (Fig. 1A). The bay (Fig. 1B) is partly sheltered by a breakwater at the mouth of the bay with the remaining stretch of 850 m and water depth of 26 m leading to the open sea. Fig. 1B shows a gridded bathymetric map of the area referenced to the mean sea level and with a resolution of 10 m that was rendered using bathymetric LIDAR data (ERDF 156 data, 2013). At the centre of the bay, existing channels have been dredged periodically since 1990 to maintain the designated depth below 17 m (Adi Associates Environmental Consultants Ltd, 2007). Elsewhere, the eastern and western parts of the bay have a mean water depth of 10 m (Axiak, 2013). The bay shows spatial variation in grain size with heterogeneous soft sediments (very fine to medium grain size) and muddy sediments at the centre of the bay, near the navigation channels.

Due to its location, the area is archetypal of a multiple use coastal environment. The area is one of the busiest coastal locations of the island and is surrounded by both residential and commercial areas. The inshore fish farm, run by Malta Fish Farming Ltd., has been in operation since 1993. This facility is in shallow waters between 8 m and 12 m at the centre of the outer bay (Fig. 1B). This is a nursery facility where gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) are cultured on formulated commercial feeds, and where a batch of the greater amberjack (*Seriola dumerili*) was held and supplemented with baitfish. In 2019, the farm had a total annual production of 719 t.

Marsaxlokk Bay is also the major base port for 70% of the Maltese fishing fleet and has various berthing facilities that include a major maritime transhipment terminal, industrial fuel storage facilities, an electricity generation plant, a commercial marine fish farm, and a land-based aquaculture facility. On the western side of the outer bay, the transhipment terminals lie just 500 m from the fish farm. These are operated continuously and have a capacity for 3.8 million TEU (twenty-foot equivalent units)[1] in its deep-water quays (total operational area of 2463 m) (Malta Freeport, 2021). In 2020, these terminals registered 1553 calls and 2.44 million TEU (Malta Freeport, 2021). Different types of cargo are handled inside the port area at the centre of the bay, whereas various maritime uses from leisure crafts, traditional vessels and trawlers are associated with the traditional fishing village in the harbour at the northern end of the bay.

Data from the weather station at the Malta International Airport showed that the dominant (18.08%) wind direction is 285° (WNW) to 315° (NW) in the Marsaxlokk bay with wind speeds that are greater than 5.7 m s^{-1} for 35.3% of the time and that rarely exceed 17.5 m s^{-1} (Hydraulics, 2007). The local wave climate is dominated by wind-generated waves from the predominant north-west winds, with tidal influence on water movement considered minimal (Hydraulics, 2007). Moreover, simulated currents in the Marsaxlokk Bay are wind-dominated relative to tidal influences, which are considered negligible (Hydraulics, 2007).

2.2. Data collection

2.2.1. Hydrographic and meteorological data

Hydrographic data was collected at the test site using an Acoustic Doppler Current Profiler (ADCP), Aquadopp Profiler

[1] 1 TEU is 6.1 m × 2.4 m × 2.6 m (length × width × height) and a maximum load of 24 tons.

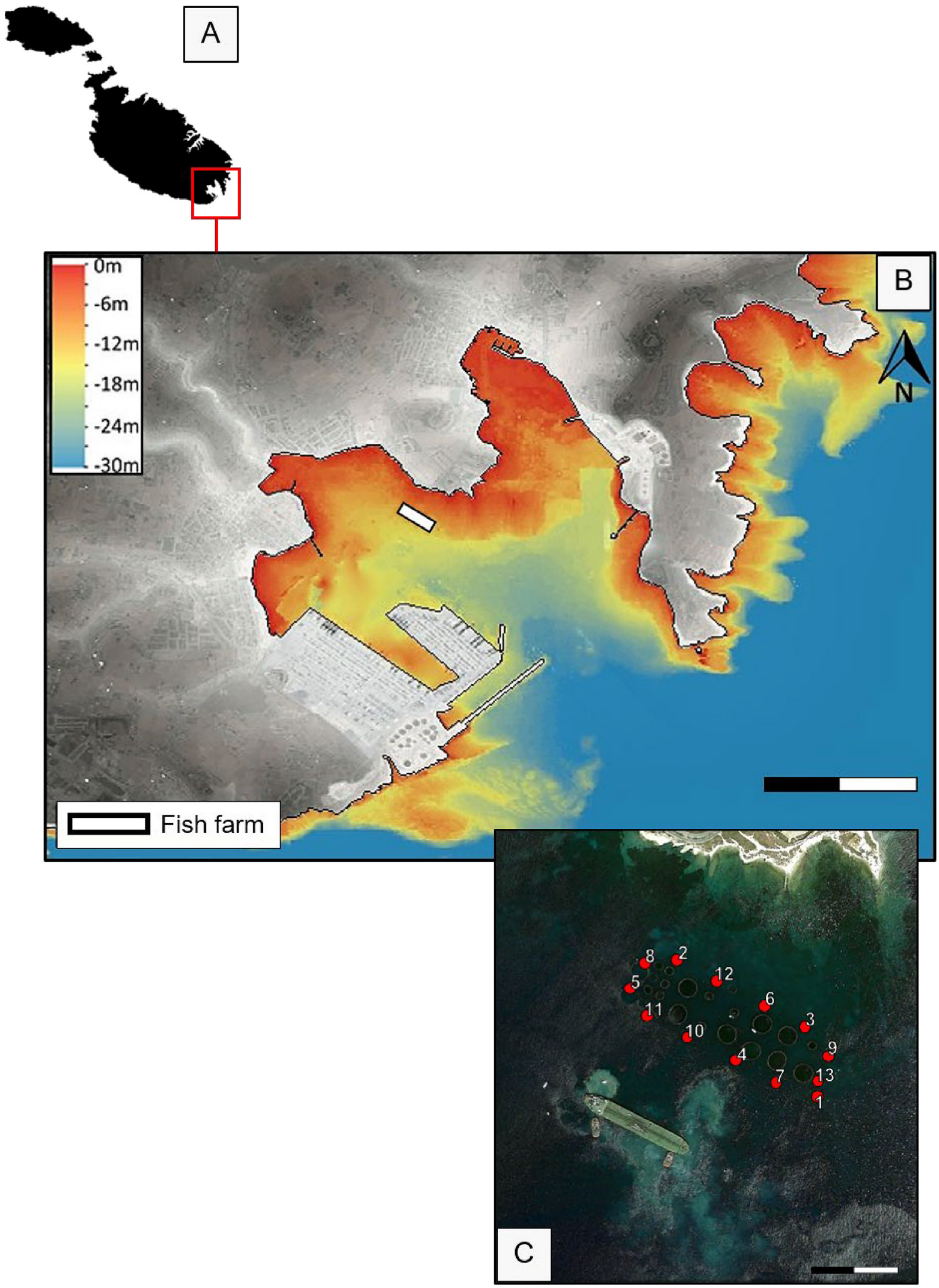

Fig. 1. A. Location of the test site within Marsaxlokk Port, southeast Malta, and B. bathymetric map of the area rendered from LIDAR data (ERDF 156 data, 2013) showing the location of the fish farm (Scale bar 1 km). C. Deployment positions of the acoustic Doppler current profiler in order of placement around the fish farm in Google Earth (Scale bar 200 m).

400 kHz (Nortek, Norway), between May 2018 and August 2019 (Table 1). The ADCP was deployed on the seabed at different sites and at different water depths next to fish cages around the fish farm (Fig. 1C). The ADCP was set an upward-direction configuration on the seabed to obtain current measurements at each one-metre water depth intervals to record hydrography through the fish farm, across a varied bathymetric profile. This allowed for accurate velocity measurements albeit with limitations in measuring the surface layer (10% of water column) due to side lobe interferences, and the near-bottom currents within the blanking distance and the height of the current meter bottom mount. Data was recorded with a temporal resolution of 20 min. The values represent an average of the collected measurements at 60 s intervals over the sampling duration.

Table 1
Sites and periods of deployment of the current profiler around the fish farm in the Marsaxlokk Bay.

Site number	Deployment date	Retrieval date	Deployment duration (days)	Latitude (deg. N)	Longitude (deg. E)	Water depth (m)
1	07/05/2018 08:20	31/05/2018 08:20	24	35.826378	14.543042	11.9
2	31/05/2018 08:40	02/07/2018 10:45	32	35.82859	14.54089	7.5
3	02/07/2018 11:00	02/08/2018 13:40	31	35.827111	14.54362	8.4
4	02/08/2018 13:59	07/09/2018 10:30	36	35.82698	14.54213	12.5
5	07/09/2018 11:35	11/10/2018 11:35	34	35.8279	14.54008	11.4
6	11/10/2018 12:00	05/11/2018 11:50	25	35.827983	14.542425	8
7	05/11/2018 12:16	05/12/2018 12:45	30	35.82675	14.54258	13.3
8	12/12/2018 13:00	17/01/2019 12:00	36	35.82852	14.54079	9.8
9	17/01/2019 13:00	07/02/2019 12:40	21	35.82747	14.54342	8.5
10	07/02/2019 14:00	06/03/2019 09:40	27	35.82718	14.54136	13
11	06/03/2019 10:20	10/04/2019 07:40	35	35.8277	14.54067	10.5
12	10/04/2019 07:45	28/05/2019 10:30	48	35.82805	14.54196	10.2
13	28/05/2019 10:50	20/08/2019 09:01	84	35.82647	14.5432	12.8

A WaveGuide sea level monitoring sensor, installed at tip of the breakwater at the mouth of Marsaxlokk Bay in March 2021, was used to measure sea level, wave height, and wave period. This radar sea level gauge measures heave with a resolution of 3 mm at a frequency of 10 Hz and wave height with an accuracy of 1 cm at one-minute intervals. The sea level sensor recorded *in-situ* range of free surface elevation as tides entered the Marsaxlokk Bay between the 1st and 7th of November 2021. This sensor is operated and maintained by the Physical Oceanography Research Group (PO-Res Group) of the University of Malta, as part of the SIMIT-THARSY project (Physical Oceanography Research Group, 2021).

Concomitant two-year meteorological data between 2018 and 2019 was extracted from the validated 'MARIA/Eta' high-resolution atmospheric forecasting system for the Central Mediterranean and the Maltese Islands that is run and maintained by the PO-Res Group. The model runs daily starting from 12.00 h GMT of the current daily and produces a 48 h forecast that has 3 h outputs (Physical Oceanography Unit, 2006). *In-situ* measurements from the meteorological station located on the breakwater at the mouth of the bay could not be used for this present study. Instead, the modelled wind forecast at 10 m above sea level at the cell centred at 35.8333°N of latitude and 14.5417°E of longitude was used.

2.2.2. Vessel data

In the present study, data from a local Automatic Identification System (AIS) receiver that was set up by the PO-Res Group was used to track the ship activity inside the Marsaxlokk Port and around the inshore fish farm. As of 2004, the AIS was mandatory for ships as per the Vessel Traffic Monitoring and Reporting Requirements Regulations (S.L.499.23) of Malta and in accordance with standards of Chapter V/19 of the SOLAS convention.

Position and speed data transmitted by these vessels were collected every 30 min to extract records between 12th April 2018 and 28th May 2019 in the Marsaxlokk Port area between 35.80°N and 35.85°N latitude, and 14.52°E and 14.57°E longitude. The AIS data provided static information on the vessel such as the ship name, the Maritime Mobile Service Identity (MMSI) code, as well as the dynamic and voyage-related details that include vessel position and navigation status.

2.3. Data analysis

This study assessed the relationship between *in-situ* current observations and modelled wind data. The *in-situ* measurements of water current magnitude and direction that were captured at different depths by the ADCP were normalised to represent depths at every 1 m. The speed and direction of measured current data at different depths and modelled wind data were standardised to 1 h temporal resolutions and correlated (Pearson Product Moment Correlation using SPSS *v*1.0.0.1327). This was carried out for every 1 m water depth downward from the uppermost near-surface layer until no statistical relationship was established. Correlations were calculated with no time delays and with hourly lags to a maximum lag of 12 h between wind and near-surface sea currents, in terms of magnitude and direction, over a whole time series to determine the effect of time delays on sea current response. Data was tested for normality using the D'Agostino-Pearson's K^2 to meet assumptions of Pearson's correlation.

The relationship between observed current speeds and values predicted by the hydrodynamic-wave model, Marine Forecasting System (MFS) (Clementi et al., 2019), was assessed at the same water depths through regression. MFS is a high-resolution open-water hydrodynamic-wave forecast available on Copernicus that runs over the entire Mediterranean region at a spatial resolution of 0.042 degrees and provides 141 unevenly spaced depth levels. The forecast from MFS was taken as at 35.8125°N of

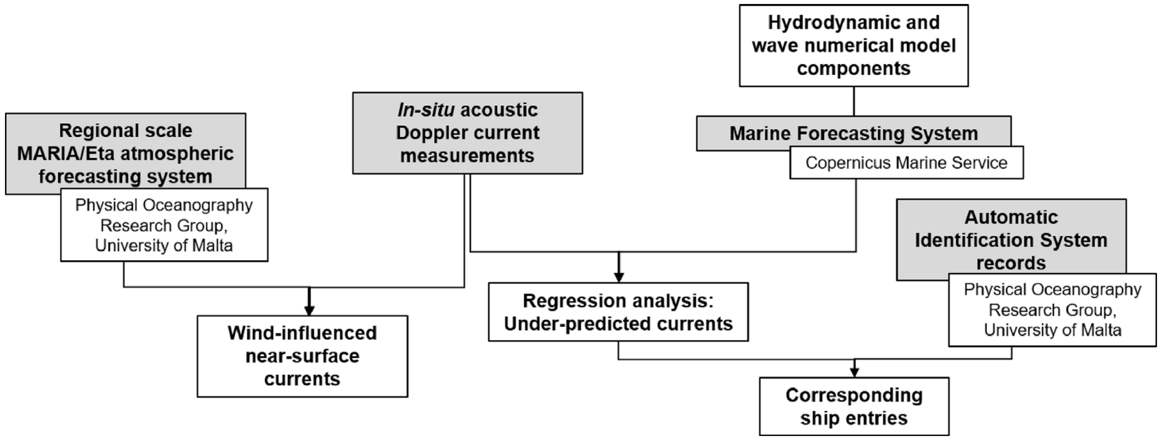

Fig. 2. Schematic illustration interrelating the atmospheric (MARIA/Eta) and the hydrodynamic-wave (Marine Forecasting System) with the observed water currents from the acoustic Doppler current profiler and ship entries from the Automatic Identification System in Marsaxlokk Bay.

longitude and 14.58333°E of latitude. This grid cell is at the land-sea boundary, specifically at the mouth of the Marsaxlokk Bay, and the closest to the area of study.

The schematic illustration in Fig. 2 conveys the main elements of the present study, specifically the atmospheric (MARIA/Eta) and hydrodynamic-wave (MFS) models, and simplifies how they have been linked to investigate the effects of wind and ship traffic on water current variability in Marsaxlokk Bay.

MFS data was only available from October 2018. Therefore, comparisons with the ADCP current values were only possible from this date onwards until the end of the study in August 2019, covering the deployment site numbers 5 to 13 (Table 1). A fixed threshold value (0.2 m s^{-1}) was set *a posteriori* as maximum residual value between 'observed' and 'predicted' values for current magnitude to identify data under-predicted by the hydrodynamic-wave model that were thus considered not explained by the atmospheric forcing variables that are assimilated into the model. This data could be explained by external forces that the hydrodynamic and wave components of the model did not account for, possibly including human-induced disturbances such as marine traffic near the ADCP deployed around the fish farm. To explain this data, the AIS records for ship activity inside the port and near the fish cages were traversed to identify any corresponding ship entries underway within a 650 m radius and within a 10-min window from the under-predicted data points. Furthermore, the frequency and the type of vessels that corresponded with the extracted under-predicted current data were identified.

3. Results

3.1. Water currents

The time-series data provides *in-situ* measurements that recorded the local currents conditions near inshore fish cages that are situated in this busy Mediterranean bay and port area, over a 16-month period available through the EMODNET repository at (https://www.emodnet-ingestion.eu/submissions/submissions_details.php?menu=39&tpd=550&step_more=9).

The current magnitude fluctuated between peaks and intervals throughout the observed periods. The highest recorded current magnitude was 1.389 m s^{-1} at site 3 in July 2018 whereas low current magnitudes (<0.001 m s^{-1}) were observed in different water depth layers repeatedly throughout the study (Supplementary 1). Intermittent data points reveal high current magnitudes in the dataset recorded by the ADCP that were only limited to and did not extend beyond single measurements. During specific periods, that include May and December 2018, higher average speeds were apparent in the near-surface layers (Supplementary 1) at the different sites around the fish farm (Table 1).

The hydrographic dataset shows that the direction of currents changed over time at the different deployment sites of the ADCP. Moreover, the data revealed variation in the direction of currents between different water depth layers, particularly between near-surface and near-bottom currents, in specific periods of observation. This temporal and spatial variation in water currents, specifically between different depth layers in the vertical water profile, provide empirical grounds for the possible influences of different and dynamic forcing factors, such as wind and ship traffic, on water currents around the static infrastructure of the fish farm.

The *in-situ* observations reveal a small constant diurnal cycle with a tidal period of 12 h in the bay (Fig. 3). Tidal fluctuations are superimposed by smaller fluctuations presumably due to swell waves, internal resonance of the particular basin and other factors. The tidal range is generally less than 0.4 m and therefore small tidal currents are expected, a trend that follows the general Mediterranean tidal fluctuation. The weak tidal influences that are expected at the mouth of the Marsaxlokk Bay reveal that water level variations seem more related to meteorological influences. This analysis of forcing factor influence on the hydrodynamic variability in this bay provides an account of the negligible tidal component and consequently, tidal effects on sea currents were not considered in the present study. Real-time water surface elevation data from the sensor is available at: (http://ioi.research.um.edu.mt/porto-stations/index.php/welcome/open/MRXB/marine/0).

3.2. Wind direction and speed

The easterly component winds from 90.0° to 112.5° were the strongest and most frequent accounting for 15% of the total predicted wind direction (Fig. 4). The wind direction was variable throughout the observation period. The corresponding time series shows stable periods and intervals of transformation between the stable stages (Supplementary 2A). The wind speed as predicted by the MARIA/Eta model ranged between 0.02 m s^{-1} and 17.97 m s^{-1} and averaged 3.62 m s^{-1} (Supplementary 2B). Throughout the study, moderate winds between 5.5 m s^{-1} and 7.9 m s^{-1}, and winds travelling faster than 8 m s^{-1}, were predominantly recorded between November and May, in 2018 and 2019. Daily atmospheric regional scale forecast for central Mediterranean is available at (http://www.capemalta.net/maria/regional/results.html).

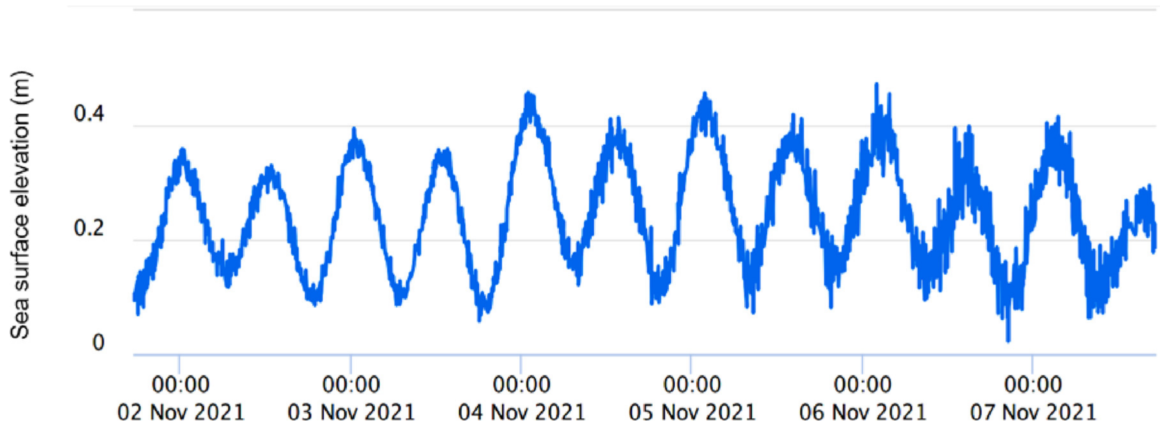

Fig. 3. Sea level variations recorded at the oceanographic station in Marsaxlokk Bay between the 1st and 7th November 2021.

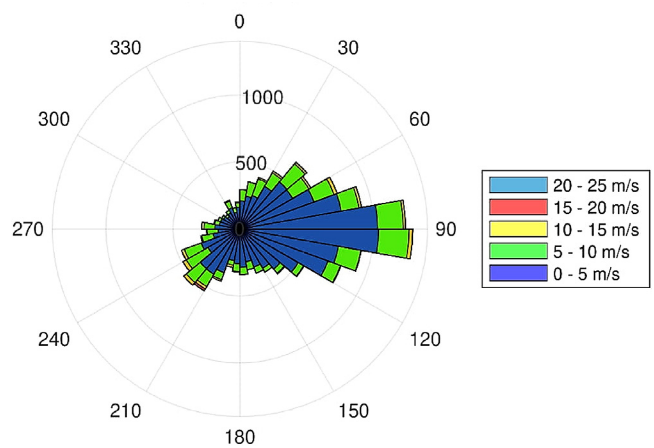

Fig. 4. Wind rose plot from the numeric high-resolution atmospheric forecasting system for the Central Mediterranean and the Maltese Islands (MARIA/Eta), at 10 m above sea level for 35.8333°N and 14.5417°E, between 2018 and 2019.

3.3. Wind and currents' relationship

The magnitude and direction of the sea currents at different water depth levels near the fish farm were correlated with the outputs of the MARIA/Eta wind model. A significant relationship was generally established between wind flow and near-surface hydrography (Table 2). Results show the correlation coefficient was usually highest for correlations with zero time lag that decayed from their maximum correlation value with increased hourly time shifts. This reveals the momentum transfer through wind stress that generates immediate response in near-surface currents, between the first and second water depth layers measured at one-metre intervals. Crossed-correlations reveal weaker relationships between forecast wind and observed near-surface current series in lagged correlations compared to those that have the same mode (zero time lag). At this point, while lagged correlations were calculated in terms of direction and magnitude, and not shown, only zero lag correlations between wind and sea currents are presented in this study.

The magnitude of the water currents was positively correlated with predicted wind velocity (MARIA/Eta) in all observed periods. However, the strength of this relationship decreased with increasing depth. A significant relationship was observed between observed ADCP currents and forecast wind (MARIA/Eta) in the uppermost near-surface layers and therefore only the statistical outcomes for the near-surface water layers are presented in Table 2.

Wind and current direction were significantly correlated at the uppermost near-surface water layer, except in July 2018 and between September and October 2018. Where there is a statistically significant relationship, the correlation between the direction of wind and currents is negative, except in August and September 2018. Generally, the relationship between wind flow and current direction decreased rapidly with increasing water depth so that current direction was less affected by wind, or not at all, below near-surface waters. These observations show the extent of effect exerted by wind forcing on the current conditions at different depths and attests to wind influences on the near-surface water currents in the Marsaxlokk Bay. Where no correlation was established or the relationship strength was weak (low r^2 value) (Table 2), current conditions around the fish farm may not be explained by meteorological effects but could be influenced and driven by other forces or processes.

3.4. Current velocity anomalies and ship traffic

The Automatic Identification System (AIS) data for the period between April 2018 and May 2019 showed that 2371 passages of vessels were recorded in the study area. The density map, produced over a regular grid with a resolution of 0.0001 degrees, illustrates the frequency of ship and boat passages in the area to highlight inbound and outbound trajectories of vessels and to describe their sailing line (Fig. 5). Ship activity was higher around the transhipment terminals and in the various inlets of the Marsaxlokk Port, notably the Marsaxlokk fishing harbour at the head of the bay. A higher frequency of vessel passages was recorded near the fish farm especially to the southwest of the aquaculture site, the location of a mooring site used for bunkering. Different types of vessels frequent the transhipment terminals, the fishing harbour and the other berthing facilities in the area (Supplementary 3). These navigate the coastal waters of Marsaxlokk Bay to carry out different activities, such as dredging, towage and bunkering, in different designated locations in the area.

The relationship between the current magnitude values predicted by the model (MFS) and those measured *in-situ* by the ADCP identified disturbances in the current state that were not explained by the Copernicus hydrodynamic-wave forecast (Fig. 6). Regression analysis between predicted and observed current magnitude values at similar water depth layers revealed that the mean absolute error decreases with increasing water depth between the near-surface and the near-bottom water currents.

There were 131 records of AIS equipped vessels within a 650 m radius of the ADCP and a 10-min window of instances

Table 2
Correlation between wind predictions from the numeric forecast model 'Malta Atmospheric and Wave Forecasting System' (MARIA) and current data, for magnitude and direction for the upper water layers at each site.

Current profiler deployment period	Distance from seabed (m)	Wind and current magnitude (m s^{-1})			Wind and current direction (degrees)		
		r	r^2	p-value	r	r^2	p-value
07/05/2018–31/05/2018	9	0.093	0.009	0.038**	0.041	0.002	0.360
	10	0.164	0.027	<0.001**	0.083	0.007	0.063
	11	0.373	0.139	<0.001**	0.166*	0.028	<0.001**
	12	0.583	0.340	<0.001**	0.403*	0.162	<0.001**
31/05/2018–02/07/2018	4	0.034	0.001	0.376	0.027	0.001	0.469
	5	0.036	0.001	0.340	0.060	0.004	0.113
	6	0.094	0.009	0.013**	0.063	0.004	0.098
	7	0.278	0.077	<0.001**	0.112*	0.012	0.003**
02/07/2018–02/08/2018	5	0.007	0.000	0.848	0.035	0.001	0.347
	6	0.045	0.002	0.222	0.066	0.004	0.077
	7	0.032	0.001	0.393	0.008	0.000	0.823
	8	0.232	0.054	<0.001**	0.020	0.000	0.592
02/08/2018–07/09/2018	9	0.024	0.001	0.499	0.054	0.003	0.133
	10	0.020	0.000	0.583	0.020	0.000	0.576
	11	0.076	0.006	0.035**	0.030	0.001	0.404
	12	0.430	0.185	<0.001**	0.188	0.035	<0.001**
07/09/2018–11/10/2018	8	0.124*	0.015	0.000**	0.025	0.001	0.481
	9	0.004	0.000	0.911	0.046	0.002	0.190
	10	0.320	0.102	<0.001**	0.015	0.000	0.677
	11	0.422	0.178	<0.001**	0.037	0.001	0.285
11/10/2018–05/11/2018	4	0.015	0.000	0.712	0.065	0.004	0.114
	5	0.052	0.003	0.202	0.134*	0.018	0.001**
	6	0.000	0.000	0.994	0.119*	0.014	0.004**
	7	0.106	0.011	0.009**	0.048	0.002	0.244
05/11/2018–05/12/2018	10	0.031	0.001	0.411	0.034	0.001	0.375
	11	0.010	0.000	0.797	0.016	0.000	0.677
	12	0.124	0.015	0.001**	0.103*	0.011	0.006**
	13	0.573	0.329	<0.001**	0.358*	0.128	<0.001**
12/12/2018–17/01/2019	6	0.039	0.002	0.288	0.056	0.003	0.128
	7	0.006	0.000	0.861	0.003	0.000	0.941
	8	0.057	0.003	0.121	0.074	0.005	0.043**
	9	0.414	0.171	<0.001**	0.194*	0.038	<0.001**
17/01/2019–07/02/2019	5	0.025	0.001	0.585	0.018	0.000	0.694
	6	0.064	0.004	0.160	0.011	0.000	0.808
	7	0.046	0.002	0.313	0.037	0.001	0.421
	8	0.272	0.074	<0.001**	0.466	0.217	<0.001**
07/02/2019–06/03/2019	9	0.073	0.005	0.063	0.020	0.000	0.605
	10	0.080	0.006	0.041**	0.001	0.000	0.973
	11	0.025	0.001	0.521	0.042	0.002	0.293
	12	0.264	0.070	<0.001**	0.131*	0.017	0.001**
06/03/2019–10/04/2019	7	0.085*	0.007	0.014**	0.044	0.002	0.204
	8	0.061	0.004	0.081	0.034	0.001	0.326
	9	0.013	0.000	0.708	0.063	0.004	0.071
	10	0.181	0.033	<0.001**	0.263*	0.069	<0.001**
10/04/2019–28/05/2019	6	0.060*	0.004	0.046**	0.105	0.011	<0.001**
	7	0.021	0.000	0.480	0.026	0.001	0.380
	8	0.135	0.018	<0.001**	0.075	0.006	0.013**
	9	0.132	0.017	<0.001**	0.169	0.028	<0.001**
28/05/2019–20/08/2019	8	0.041	0.002	0.091	0.010	0.000	0.684
	9	0.012	0.000	0.628	0.026	0.001	0.296
	10	0.023	0.001	0.352	0.030	0.001	0.219
	11	0.255	0.065	<0.001**	0.144*	0.021	<0.001**

r represents the Pearson coefficient of correlation and r^2 signifies the coefficient of determination.
*Shows negative Pearson correlation.
**Correlation is statistically significant at $p < 0.05$ level (2-tailed).

when data for predicted current magnitude was in poor agreement with the *in-situ* measurements. These vessel records corresponded with under-predicted current magnitude values when the ADCP was deployed at site numbers 9 to 13, excluding site number 12. Most of these records (87%) were registered by the ADCP at site 13 between 8th June and 19th July 2019. The vessel typology varied from a bunkering barge of 97 m LOA to a pilot boat, 11 m LOA (Supplementary 3). The maximum draught of these vessels ranged between 3 m and 6.2 m, not including the missing information for the pilot boat, BRAVO I, in Supplementary 3. The bunkering barge, 'SANTA ELENA' ($n = 61$), had the highest frequency of records, which was followed by the dredging vessel ($n = 46$). An apparent higher frequency of vessels corresponded with under-predicted *in-situ* measurements at the near-surface water layers (Fig. 7). The under-predicted near-bottom currents between 8 m and 11 m at the ADCP deployment site 13 were linked with the bunkering barge, 'SANTA ELENA', the dredger, and the tanker 'SPIRO F'.

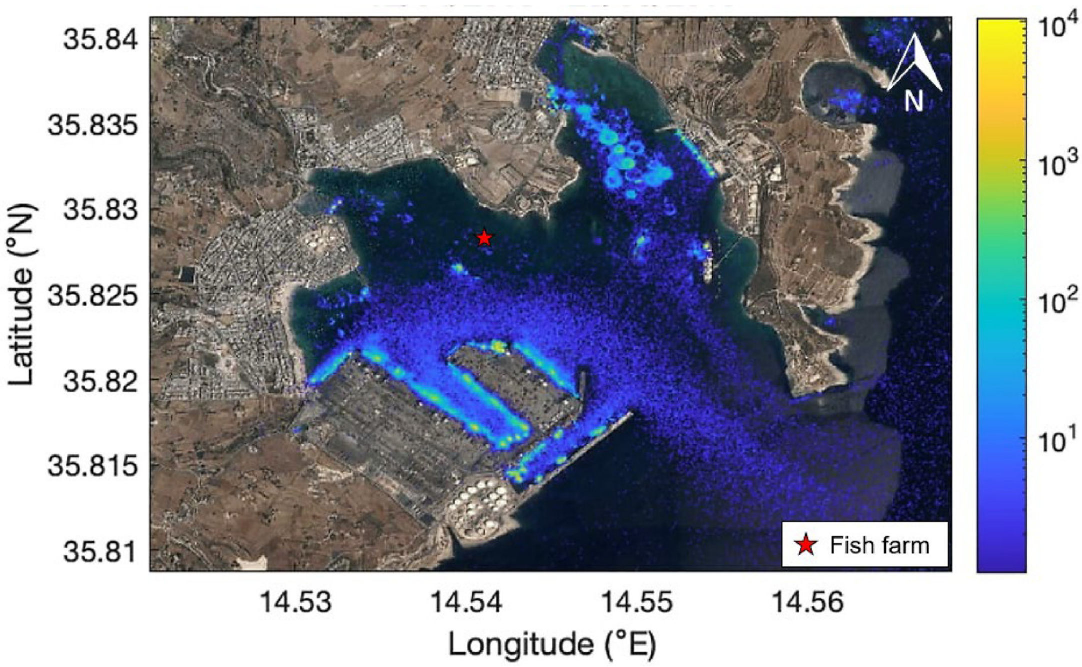

Fig. 5. Density map of ship records from the Automatic Identification System in Marsaxlokk Bay, between 12th April 2018 and 28th May 2019, produced over a regular grid with a resolution of 0.0001 degrees.

4. Discussion

This study contributes evidence for the relevance of wind-driven forces on near-surface currents in this multiple use coastal environment. Moreover, it identifies occurrences of under-predicted currents in this Mediterranean bay and port area that could be explained by ship traffic and activity. Therefore, this work provides insight into the physical forces that could contribute towards sea current disturbances and that would help describe the hydrodynamics in this busy coastal area. These findings contribute knowledge about the relevance of natural and anthropogenic forces on water movement surrounding inshore marine fish farms in the Mediterranean. This provides an appreciation for the distinct wind and ship-influenced hydrodynamic effects, considering the implications for the development of marine aquaculture and spatial planning in similar coastal spaces.

4.1. Wind-influenced currents

This observational study revealed variable currents between the different ADCP deployment sites around the fish farm and across a vertical water profile in Marsaxlokk Bay. Firstly, spatial differences in water movement around the cages would be anticipated due to the infrastructure and the orientation of the fish farm (Hartstein et al., 2021). The shadowing effects of cages have different implications for waste dispersion, production (Hartstein et al., 2021) and fish behaviour (Johansson et al., 2014), within the farm. The established correlation between wind and near-surface water current velocities attests to the influence of this forcing factor on water movement in this bay. The temporal differences in hydrography, particularly in the near-surface waters, show that these currents are modulated by the seasonality of their driving force in Marsaxlokk Bay. This corresponds with the variable winds that have been described for this area. It substantiates findings of dominant wind-induced currents and inconsiderable tidal influences (Hydraulics, 2007). These computed predictions are corroborated by the relationship established between the observed current measurements and the wind forecast of the MARIA/Eta model in the present study. Elsewhere in the Mediterranean region, complex and heterogeneous flows have also been described in bays where near-surface currents are predominantly influenced by wind (Grifoll et al., 2014; Llebot et al., 2014; Cerralbo et al., 2015; Balsells et al., 2020).

These observations of wind-driven near-surface currents have important implications for the development of marine aquaculture. Intermittent and strong water currents driven by strong wind events could influence the traditional circular schooling behaviour of caged fish if current velocities are altered within the cage (Johansson et al., 2014). This could elicit behavioural response, particularly from juvenile fish at these inshore nursery sites, with potential effects on welfare and production efficiency (Johansson et al., 2014). Moreover, strong wind effects on near-surface currents could drive differences in water quality within the water column (Hartstein et al., 2021) or accentuate flows to improve exchange rates (Holmer, 2010) and disperse wastes (Holmer, 2010; Klebert et al., 2013). This observational study also corroborates predictions that winds are not likely to influence near-seabed currents (Hydraulics, 2007). However, vertical variations in hydrography with strong current occurrences closer to the seabed and low coefficients of determination indicate external processes or forces that could act to drive or influence these currents. These currents could have distinctly different impacts, such as the mobilisation and suspension of sediments, and important implications for marine aquaculture that would need consideration. At least, an understanding of these effects on hydrodynamics and their implications for cage culture and production can be a support tool for optimised feeding practices and management strategies.

4.2. Ship-related currents

Although dominated by the most powerful and perpetual driving factor (wind), hydrodynamic behaviour and response depend on a combination of forcing factors (De Marchis et al., 2014; Grifoll et al., 2014), some of which considered in this study for a more precise description of the system. Intermittent and

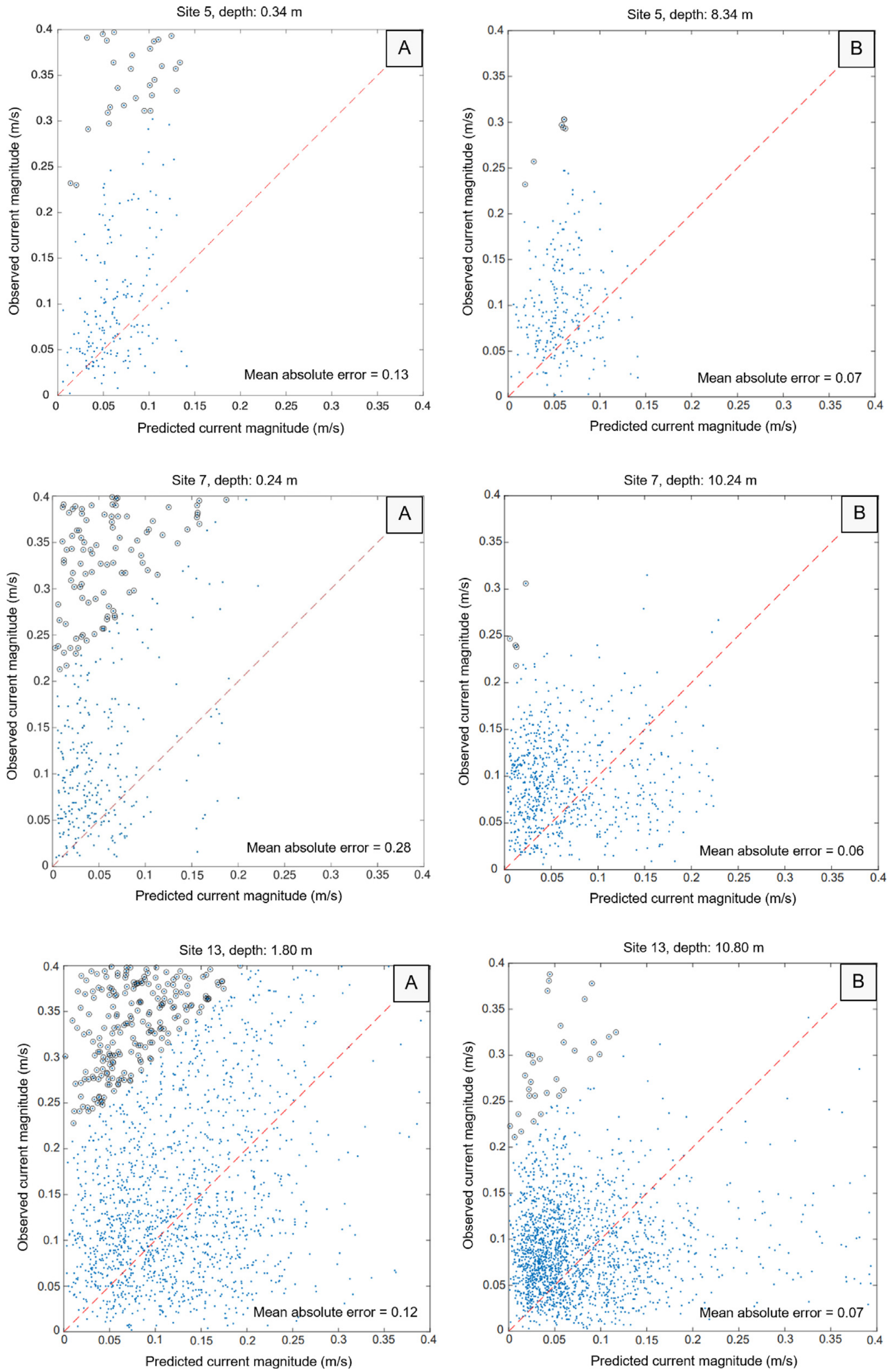

Fig. 6. Relationship between *in-situ* observations of seawater current magnitudes and predicted values from the hydrodynamic-wave forecast model, 'Marine Forecasting System' (MFS), for a subset of sites (5, 7 and 13) and water depth levels (near-surface (A) and near-bottom (B)). Marked data points were identified as under-predicted current magnitude values.

specific under-predicted currents that were not explained by meteorological effects were associated with different ship and boat typologies that were operating, navigating or manoeuvring in the bay. The passage of deep-draft cargo ships involved in transhipment and bunkering, and dredging operations near the fish farm in the Marsaxlokk Bay could be cause for near-seabed disturbances. Notwithstanding the possibility of propeller-induced suspended sediments, near-seabed currents could also cause

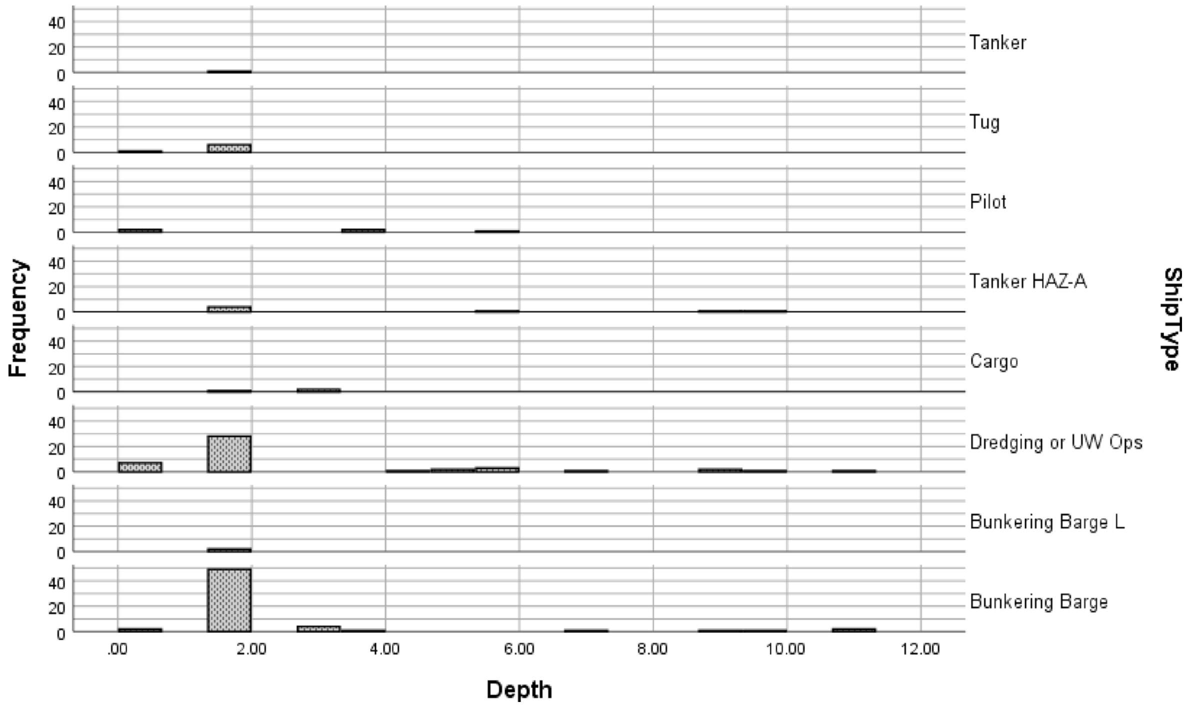

Fig. 7. Frequency of vessels corresponding to under-predicted current magnitude values predicted by the hydrodynamic-wave forecast model, 'Marine Forecasting System' per water depth level.

sediment resuspension (Cromey et al., 2012). The short-term effects of suspended sediments on water quality, fish stress and behaviour are well-documented (Kjelland et al., 2015) and therefore, validated ship-generated near-seabed hydrodynamics could have considerable implications for aquaculture production and management, especially in heavily industrialised coastal areas.

Previous studies revealed that the magnitude and behaviour of currents in shipping waterways depend on ship characteristics, including vessel type, size and hull shape (Bellafiore et al., 2018; Mao and Chen, 2020; Mao et al., 2020). The identified ship typologies would have distinct hydrodynamic effects within the vertical water gradient. At the surface and within the water column, different hydrodynamic disturbances could characterise floating collar and net deformations, cause nuisance to farm structures in terms of engineering and economic effects (Klebert et al., 2013; Faltinsen and Shen, 2018), and have direct effects on fish behaviour and welfare inside the cage (Klebert et al., 2013; Johansson et al., 2014). Consideration for these distinct hydrodynamic effects is critical for the development of marine aquaculture, especially where this exists in multiple use areas and it is challenged by pre-existing, traditional and socioeconomically significant maritime industries. This identifies the need for further research on the interactions between different coastal users and the hydrodynamic environment, and then the resultant implications for cage aquaculture.

Conclusion

This study reveals variable seawater currents in dynamic coastal spaces where multiple maritime activities can influence farm-scale hydrodynamics. This research describes causes for distinct hydrodynamic disturbances that may need to be investigated further for a more detailed description of seawater current complexities. Dominant and perpetual wind forcing, which is already a fundamental component of hydrodynamic models, influenced near-surface currents in this semi-enclosed bay. However, intermittent seawater current disturbances could not be explained by meteorological influences but rather associated with maritime traffic and operations in this crowded coastal space. Therefore, to provide a detailed account of local farm-scale hydrodynamics, anthropogenically-derived forcing variables on water movement through fish farms should be accounted for in these dynamic environments. Decision-support tools should consider these real-world complexities in processes and policies for the effective management and development of marine aquaculture in these complex coastal areas. Under these circumstances, marine aquaculture can be influenced by different wind and ship-influenced impacts that need to be assessed further to understand how to predict and mitigate these hydrodynamic effects effectively. Where the expansion of marine aquaculture is increasingly challenged by strong wind events and coastal maritime activity, these variable and dynamic forcing factors need further representation.

CRediT authorship contribution statement

Karl Cutajar: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Adam Gauci:** Conceptualization, Formal analysis, Resources, Visualization. **Lynne Falconer:** Conceptualization, Funding acquisition, Writing – review & editing. **Alexia Massa-Gallucci:** Investigation. **Rachel E. Cox:** Investigation. **Marina E. Beltri:** Investigation. **Tamás Bardócz:** Project administration, Funding acquisition. **Alan Deidun:** Resources, Writing – review & editing. **Trevor C. Telfer:** Conceptualization, Funding acquisition, Writing – review & editing.

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

I have shared the link to data in the manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2023.102855.

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