Original Article

Hydrodynamics of nearshore coastal waters: Implications for marine cage farming in Kenya

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Abstract
Hydrodynamic characteristics are important considerations in the design of cages used for fish farming in nearshore marine environments. The hydrodynamics of sites in mangrove creeks and comparatively open water channels in Kilifi and Kwale Counties in Kenya were sampled across tidal cycles and seasons using an Acoustic Wave and Current Profiler (AWAC). Water temperature ranged between 25.9 °C and 33.0 °C, and was lower in deeper areas with larger tidal heights than in shallower areas with smaller tidal heights. The water column height ranged between 9.68 - 14.69 m at Kijiweni, 1.16 - 6.7 m at Kibokoni and Tsunza, and 0.72 - 2.57 m at Dabaso. Maximum current speeds were 0.83 - 0.87 m/s at Kijiweni, 1.1 m/s at Kibokoni, 0.89 m/s Tsunza, and 0.34 m/s at Dabaso. Wave height reached 0.35 and 0.36 m at Kijiweni, 2.7 m at Kibokoni, 1.3 m at Tsunza, and 1.6 m at Dabaso. The considerable difference in hydrodynamic characteristics between the sampling sites indicate that cages for marine fish farming should be designed specifically for local conditions in mangrove creeks and Cages for fish farming therefore require specific design and structural features depending on the local hydrodynamic conditions.

Keywords: hydrodynamics, marine, cage, culture, Kenya

Introduction
Capture fisheries on the east African coast provide support to a large number of communities. They are mostly artisanal, underdeveloped, over exploited and associated with coral reef, seagrass and mangrove ecosystems that are faced with challenges of degradation and climate change effects among other stressors (McManus *et al.*, 1997; Jiddawi and Öhman, 2002; Kaunda-Arara *et al.*, 2003; Worm *et al.*, 2006; McClanahan *et al.*, 2008; Mirera *et al.*, 2013). Indeed, primary producers working in the agriculture, forestry and fisheries sectors are more vulnerable to climate change since they are dependent on climate-sensitive natural resources; a situation which therefore impacts food security and livelihoods (IPCC, 2007; Cooper *et al.*, 2008; Stokes and Howden, 2010).

Global fish consumption has increased significantly since 1960 (9.0 kg per capita per year) to current (20.5 kg per capita per year). Per capita fish consumption in Africa is nearly half the global average (9.9 kg per capita) and accounts for 30 – 50 % of all the animal protein in many coastal countries (UN Nutrition, 2021). In the early 1980s per capita fish consumption in Kenya was estimated at 4.3 kg whereas demand for fish was estimated at 9.5 kg/person/year which implied a deficit in fish production that needed aquaculture intervention (Balarin, 1985). Currently, per capita fish consumption is estimated at 8 kg/person in Tanzania and 5.5 kg/person in Kenya thus creating a fish deficit of 230,000 MT in Tanzania and 150,000 MT in Kenya (Pauly *et al.*, 2003; FAO, 2018). Globally it has been observed that low fish supply could lead to malnutrition, under nutrition, and micronutrient deficiencies, which will consequently lead to poor health (Golden *et al.*, 2016). It is therefore evident that addressing food and especially protein insecurity in east Africa requires a sustainable and multi-faceted approach rather than dependency on freshwater systems where most of the aquaculture is currently practiced, wild fish capture, fish imports and terrestrial agriculture that depends on rain and other water sources that are impacted by climate change (Mmochi, 2015). Despite aquaculture being one of the frontiers for food production in the world (UN Nutrition, 2021), it is faced with several limitations with regard to sustainable development that need to be addressed (Troell *et al*., 2009).

Consequently, there is a need to develop strategies to adapt and mitigate climate change impacts and reduce social vulnerability from fish deficits to be able to attain the United Nations Sustainable Development Goal (SDG 14). Mariculture development is one of the strategies proposed to reduce pressure on near-shore fisheries in coastal east Africa (Troell *et al*., 2011). Mariculture in Kenya was conceptualized in 1976 through farming of prawns in intertidal earthen ponds at Ngomeni after failure of soil suitability tests at Dabaso in addition to seasonal fluctuations in temperature and salinity that impacted growth and survival (FAO, 1977). To date mariculture production has remained low in the country even though more species have been recruited into culture (Mirera, 2011, 2019; Mirera *et al*., 2020). Also, progress has been made in development of hatcheries to supply fingerlings to farmers (e.g. National Mariculture Resource and Training Centre (NAMARET, Shimoni). However, there is a need to focus on suitability of sites assessments for cage farming.

The development of marine cage farming will complement previously used intertidal earthen ponds in mangrove systems mainly used to farm milkfish, mullets, marine tilapia, mud crab and prawns extensively at small scale (Mirera, 2011, 2019; Mmochi, 2015). To embrace marine cage farming, a holistic knowledge of the ocean systems (near shore and offshore) is required to help tap into the Blue Economy potential and contribute to the sustainable development agenda (Österblom and Folke, 2013). Therefore, there is need for data on the physical and chemical dynamics of the ocean waves and currents in coastal creeks, channels, estuarine river systems, near shore and deep water systems to inform cage farming and ocean governance (Campbell *et al*., 2016; Halpern *et al*., 2019). Hydrodynamic characteristics like multidirectional, nonlinear combination of both waves and currents will inform cage engineering designs (mooring systems, cage shape, floater system, tension response, net blockage) through development of numerical models to cost effectively withstand extreme conditions and provide a suitable fish growing environment (Aarnses, 1990; Gignoux and Messier, 1999; Colbourne and Allen, 2001; Faltinsen and Shen, 2018). It is recognised that industrial marine cage fish farming is young globally but has significantly advanced in many regions of the world other than east Africa where it produces 6.6 million tons of fish per year (FAO, 2020). Indeed, cage technology genesis is traced back to the Antlantic salmon farms in Norway and Scotland in 1960s and 1970s respectively and has benefited from innovations over the years to achieve the currently engineered structures available in the market (Fredheim and Langan, 2009; Tilseth *et al*., 1991; Bao-Tong, 1994; Chen, 2007).

Using previously designed cage structures and learning from other regions like Norway, and understanding the prevailing physical and chemical dynamics of coastal sites in east Africa will inform mitigation measures through cage design, deployment, management, culture system and species to be farmed (Neori *et al*., 2004; Troell *et al*., 2009; O'Donncha *et al*., 2013). Studies undertaken in other regions indicate that water exchange rate can reduce to approximately 59 % due to increased bottom friction from suspended aquaculture in marine bivalves indicating that drag net effect influence water exchange rate and renewal of nutrient and food supply (Grant and Bacher, 2001; Shi *et al*., 2011; Cranford *et al*., 2014). Similarly, feed spills, cage waste diffusion and disposition is affected by direction and velocity of water current therefore influencing distribution of particulate organic wastes that may affect the health of benthic organisms and habitats (Holmer and Kristensen, 1994; Findlay *et al*., 1995; Wu, 1995; Petrell and Alie, 1996; Karakassis *et al*., 2000; Abreu *et al*., 2009; Faltinsen and Shen, 2018). A good current flow will ensure sufficient water exchange (good oxygen supply and well-being of fish) in a cage system.

Provision of hydrodynamic data will ensure that cage systems are installed properly to mitigate challenges associated to placement of net cage systems in areas that experience seasonal monsoon seasons and unpredictable wave behaviour or local tidal and strong ocean currents (Kawakami, 1964; Milne, 1972). The stability of marine cage culture systems will cushion farmers from major economic losses due to damages and collapses of floating fish farms that lead to escape of fish, breaking of mooring lines, anchor pull out or sliding, leading to cage movement to undesired locations with possible collisions with other maritime users, contacts between chains or ropes with the fish net leading to net tears (Faltinsen and Shen, 2018). Therefore, the current study sort to document the hydrodynamic characteristics of different near shore marine waters in coastal Kenya with the aim of delineating salient features (like depth, current strength, direction, wave height, tidal height and temperature) to inform site selection, design and deployment for marine culture cages.

Kibokoni Umoja to Tsunza Pennisula was 109 km; and from Tsunza to Kijiweni mariculture cages, Shimoni was 92 km. Kijiweni 1 and 2 were separated by a distance of less than 50 meters. The sites were categorized into three, based on the habitat and perceived hydrodynamic characteristics: (1) mangrove channels; (2) relatively sheltered near shore; and (3) sheltered creek/bays. Detailed characteristics of each of the sites is provided in Table 1.

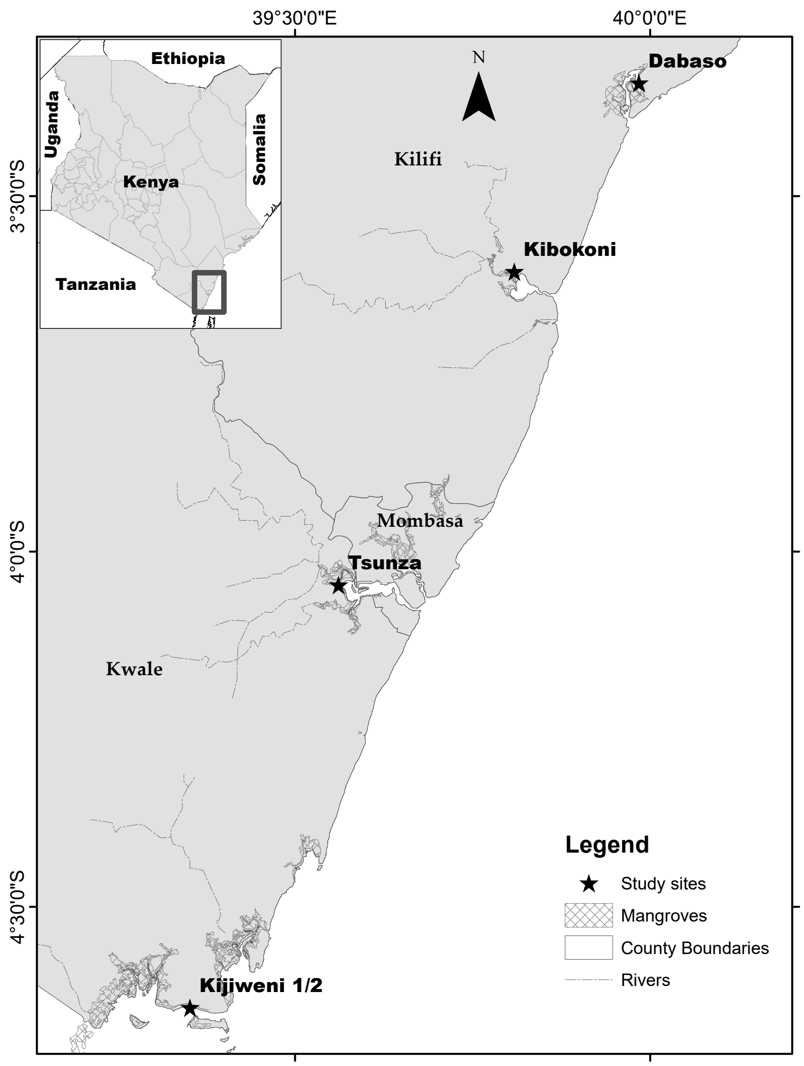

Figure 1. Map of the Kenyan coast showing the potential floating cage sites.

Methodology

Study sites

The study assessed the suitability of near shore marine waters for cage culture in Kenya. A total of five sites from the two counties of Kwale and Kilifi were involved in the study (Fig. 1). The distance between the study sites varied. From Dabaso at Mida Creek to Kibokoni Umoja group at Kilifi Creek was 54 km; from

Experimental design

Acoustic Wave and Current Profiler (AWAC)

The study used an Acoustic Wave and Current profiler (AWAC), model WAV 7499 developed by NORTEK to obtain hydrodynamics characteristics at the potential cage sites. AWAC has the capability to measure tidal variation (m), waves (m), temperature (^{O}C), current speed (m/s) and direction (degrees). Quality control

Table 1. Characterization of the different sites assessed for cage suitability using hydrodynamic parameters along the coast of Kenya.

Study sites/ Characteristics	Shimoni	Mwache creek	Mida creek	Kilifi creek
Location	**Kijiweni**	**Tsunza**	**Dabaso**	**Kibokoni**
County	**Kwale**	**Kwale**	**Kilifi**	**Kilifi**
Description	- Relatively open near shore waters - Thin mangroves dominated by Sonneratia alba and Avicennia marina - Substrate is mud sand - Bathymetry has gentle slope near shore but drastically steep ocean wards	- Sheltered mangrove channel - Dense mangrove species dominated by Rhizophora mucronata and Ceriops targal - Mud substrate - Bathymetry is gentle sloping	- Sheltered mangrove creek - Dense mangrove species dominated by Rhizophora mucronata and Avicennia marina - Mud substrate - Bathymetry is gentle sloping with pockets of channels	- Sheltered mangrove channel - Dense mangrove species dominated by Rhizophora mucronata and Ceriops targal - Mud substrate - Bathymetry has gentle slope near shore but drastically steep ocean wards
Fishing activities	- Artisanal fishing of different marine species mainly rabbitfish	- Artisanal fishing dominated by prawns	- Artisanal fishing dominated by snappers	- Artisanal fishing dominated by prawns and mud crabs
Mariculture activities	- Seaweed farming - Interest in cage farming	- Pond milkfish farming - Interest in cage farming	-Mud crab farming -Interest in cage farming	- Prawn farming, marine tilapia - Interest in fish cages

on data was conducted by the use of storm-64 software while data retrieval used AWAC AST software. The AWAC system can resolve waves from 1 to 100 seconds and measure current speed and direction in 1 m thick layers from the bottom to the surface. The AWAC equipment was deployed at the maximum recorded depth of the different study sites to collect data over a period of 4 – 19 days to capture spring and neap tide variation. Seasonal variability (NEM and SEM) was captured at one site that was relatively exposed (Kijiweni).

Equipment was prepared for use by assembling the frames using bolts and nuts and bolting the battery that runs the equipment onto the frame. It is then connected to a laptop using a serial port connector cable and configured using AWAC AST software to collect data. The AWAC equipment is carried to the site by boat and lowered to the ocean floor with the help of divers where it would remain for the whole experimental period (4-19 days). Weights were added to enhance sinking capacity and the equipment was anchored at the bottom with more weights to minimize the tilt effect (tilt angle to be less than 30 degrees at all times). A buoy was attached to the AWAC with rope for easy visibility by any other ocean users and for easy identification during retrieval.

Sampling design

The Kenyan coast is characterised by neap and spring tides which influence movement of water to the shore. Also, the coast experiences a tropical climate influenced by monsoon winds with two distinct seasons (NEM and SEM). The NEM is characterized by hot and calm weather and the SEM by strong winds, cool temperatures and rough seas (Linden and Lundin, 1996). Sampling was designed to capture data for the different seasons and tidal cycles to inform cage culture interventions (Table 2). To provide a broader view of the effect of tide and season on hydrodynamic characteristics, sampling was carried out for shorter periods of four days (covering only one neap of spring tide) and long periods of 19 days (covering full neap and spring tide cycles). At one site sampling was repeated after a year to assess if there were variations between years. The AWAC captured the same data for all sites even though sampling days were different at sites. It was anticipated that such robust sampling could provide data that could inform future site assessments for cage farming.

Stakeholder involvement was conducted through focus group discussions with the ocean users at each site, especially fishermen, to identify the most viable areas. This involved identification of sheltered areas, areas not close to known fishing areas and navigation routes, and areas that remained relatively deep at low tides (Beveridge, 2004). Random sampling was undertaken using a handheld eco sounder to establish depth gradients (Turner, 2000). Before deployment, fishers were engaged to monitor the equipment as a mitigation against vandalism.

Table 2. Acoustic wave and current profiler deployment period (days) and season at the different study sites on the coast of Kenya.

Sampling sites	AWAC deployment period (days)	AWAC deployment Month	AWAC deployment season
Shimoni, Kijiweni 1	14	March	Northeast Monsoon
Shimoni, Kijiweni 2	19	July	Southeast Monsoon
Kilifi creek, Kibokoni	14	February	Northeast Monsoon
Mwache creek, Tsunza	4	September	Northeast Monsoon
Mida creek, Dabaso	4	September	Northeast Monsoon

Data analysis

The AWAC data was analyzed and visualized using the programming and numeric computing platform MATLAB and presented graphically.

Decomposition of tidal currents

Tidal current velocities measured by the AWAC profiler were decomposed in order to determine the horizontal velocity components within the main channels. Main direction of flow was determined by plotting current velocities against respective directions. This was also used to determine the dominant current velocities during the period of measurements. The along channel velocity component (u) was determined from the current velocity record as

$$u = U\cos\left(\pi\frac{\alpha}{180}\right) \tag{1}$$

The cross-channel velocity component (v) was determined by using the equation

$$v = U\sin\left(\pi\frac{\alpha}{180}\right) \tag{2}$$

Where U is the current speed record and α is the direction angle measured in degrees.

Harmonic analysis

Harmonic analysis was carried out to establish the influence of the external factors on water velocity. The analysis is a mathematical method of extracting sinusoidal components of specific frequencies from, e.g. a water level record. In this case, it was based on the "method of least squares". Instead of fitting a straight line to the data by varying its slope and intercept, a set of cosine (or sine) curves with given frequencies ω were fitted by varying amplitudes and phases, minimizing the sum of deviations from the original curve.

Given a time series *Z* (*t*) of data points, the tidal part can be expressed as a combination of sine and cosine functions (*cf*. Dronkers, 1964) as:

$$Z(t) = \sum_k a_k \sin(\omega_k t) + \sum_k b_k \cos(\omega_k t) \tag{3}$$

The value of ak and bk can be calculated for the given frequencies, ωk by minimizing the sum of squares of the differences between the assumed function and the given time series Zn.

Least square fit requires that the following function is

$$f(a_k, b_k) = \sum_{n=1}^{N}\left(z_n - \sum_k a_k \sin(\omega_k t_n) + \sum_k b_k \cos(\omega_k t_n)\right)^2 \tag{4}$$

This requirement is satisfied by

$$\frac{\partial f}{\partial a_i} = 0 \qquad i = 1,\ldots,k \tag{5}$$

and

$$\frac{\partial f}{\partial b_i} = 0 \qquad i = 1,\ldots,k \tag{6}$$

Where

$$\frac{\partial f}{\partial a_i} = -2\sum_{n=1}^{N}\cos(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n)\right) = 0 \tag{7}$$

and

$$\frac{\partial f}{\partial b_i} = -2\sum_{n=1}^{N}\sin(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n)\right) = 0 \tag{8}$$

The above equations can be rewritten as

$$\sum_k a_k \sum_{n=1}^{N}\sin(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N}\sin(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \sin(\omega_i t_n) \tag{9}$$

$$\sum_k a_k \sum_{n=1}^{N}\cos(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N}\cos(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \cos(\omega_i t_n) \tag{10}$$

This can be simplified by introducing the notation

$$C_{in} = \cos(\omega_i t_n),\ S_{kn} = \sin(\omega_k t_n) \tag{11}$$

$$\sum_k a_k S_{kn} C_{kn} + \sum_k b_k S_{in} S_{kn} = \sum_n Z_n S_{in} \tag{12}$$

$$\sum_k a_k C_{kn} C_{kn} + \sum_k b_k C_{in} S_{kn} = \sum_n Z_n S_{in} \tag{13}$$

Results

Temperature and tidal variation

Relatively sheltered near shore waters (Shimoni – Kijiweni)

The depth of water at low tide was higher in Kijiweni 1 (12 meters) compared to Kijiweni 2 (8 meters) (Table 3). Higher variation in daily temperature was observed in Kijiweni 1 compared to Kijiweni 2 (Fig. 2 A, B). A consistent incremental trend was observed in temperature in Kijiweni 1 sampling site with a minimum of 25.9 °C, maximum of 27.6 °C and an average of 26.64 ± 0.37 °C. Kijiweni 2 recorded a minimum temperature of 28.1 °C, maximum 28.93 °C and an average of 28.42 ± 0.14 °C (Table 3). There was a difference in the behaviour of daily water column heights observed in the different sampling sites with clear distinctions between neap and spring tides (Fig, 2 C, D). The highest water column height in Kijiweni 2 was 13.568 m and the lowest 9.684 m, 14.691 m and 10.894 m respectively for Kijiweni 1 (Fig. 2 C, D).

Mangrove creek channels (Kibokoni and Tsunza)

Temperature variations at Kibokoni mangrove channel showed a distinct trend that resonated well with neap and spring tides with a maximum of 33.0 °C, minimum of 29.69 °C and an average of 30.98 ± 0.69 °C, while the highest water column height was 6.7 m and lowest 3.1 m (Fig. 3 Kibokoni A, B). At Tsunza, the sampling period was four days and temperature variations were minimal and lacked a trend with a maximum of 29.4 °C, minimum of 27.8 °C and an average of 28.64 ± 0.12 °C (Fig. 3 Tsunza A). Similarly, the highest water column height at Tsunza was 4.46 m and lowest 1.16 m but there was no tidal trend (Fig. 3 Tsunza B).

Mangrove creek bay (Dabaso)

Over the four days sampling period, temperature fluctuated between a maximum of 30.2 °C, minimum of 27.5 °C and an average of 29.54 ± 0.48 °C . The highest recorded water column height was 2.57 m and the lowest 0.72 m (Fig. 4). No specific trend was observed in the variation of the two parameters.

Tidal current speed dynamics

Relatively sheltered near shore waters (Shimoni – Kijiweni)

Water currents in the area can be classified as unidirectional caused by tides and wind. At Kijiweni 2 the current had a maximum speed of 0.8690 m/s and spread towards northeast (NE) or seawards and northwest (NW) or landwards (Fig. 5A-Direction) while in Kijiweni 1 maximum speed was 0.83 m/s and spread towards the west (W) or landwards (Fig. 5B- Direction). Current speed across the channel (V) was relatively lower than along the channel (U) (Fig. 5A -U&V, B- U&V). Flood (incoming) current dominated the site that led to an inverse correlation of the V-Velocity vs U-Velocity (Fig. 5 A – V vs U, B – V vs U). There were observed variations in wave heights over the two sampling points with highest wave height of 0.36 m in Kijiweni 2 (Fig. 6 A-W) and 0.35 m in Kijiweni 1 (Fig. 6 B-W).

Table 3. Hydrodynamic characteristics obtained in the four assessed sites along the coast of Kenya.

		Sampling sites				
Parameter	**Details**	**Kijiweni 1**	**Kijiweni 2**	**Kibokoni**	**Tsunza**	**Dabaso**
Current (m/s)	**Direction**	**W - Landwards**	**NE-seawards NW-landwards**	**SE-seawards**	**NE- seawards**	**NW – landwards E - landwards**
	Max V (across channel)	0.64	0.65	0.75	0.49	0.24
	Max U (along channel)	0.83	0.869	1.113	0.89	0.344
	Bottom water	0.541	0.41	1.195	0.89	0.344
	Intermediate	0.584	0.45	-	-	-
	Surface water	0.869	0.815	1.113	0.89	0.344
Wave height (m)	Mean	0.35	0.36	2.7	1.3	1.61
Depth (m)	At low waters	12	8	6.7	4.1	2.0
Tidal height (m)		4.0	3.89	3.6	3.42	1.87
Temperature (°C)	Max	27.6	28.93	33.0	29.4	30.2
	Min	25.9	28.1	29.69	27.8	27.5

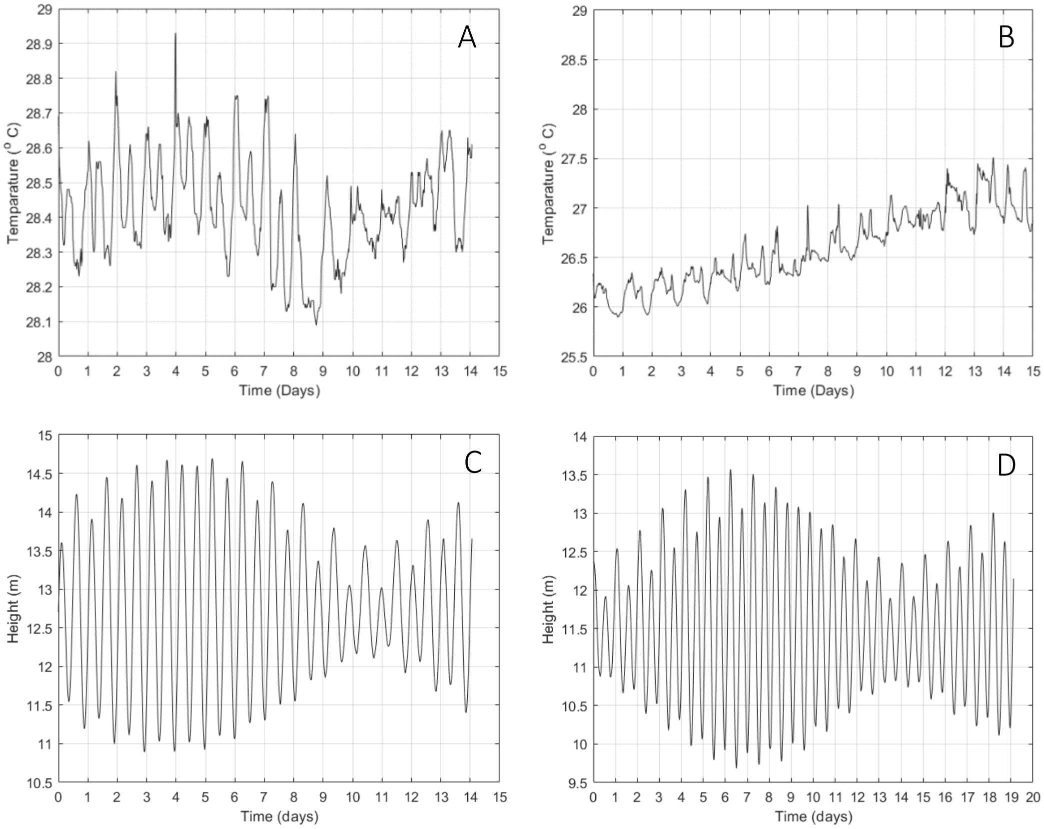

Figure 2. Water temperature (A and B) and water column height (C and D) variation in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored for two different points (Kijiweni 2-AD, Kijiweni 1-BC) for a 19 days sampling period.

Mangrove creek channels (Kibokoni and Tsunza)

The maximum current speed at Kibokoni was 1.113 m/s flowing towards the southeast or seawards (Fig. 7 A, C, E) and Tsunza 0.89 m/s flowing towards the east northeast or seawards (Fig. 7 B, D, F); an indication that ebb or receding currents dominate at the two sites. The relationship between V-Velocity vs U-Velocity at Kibokoni indicates a negative (inverse) relationship (Fig. 7 G) while that of Tsunza indicates a positive (direct) relationship (Fig. 7 H). The maximum wave height recorded at Kibokoni was 2.7 m (Fig. 8 K-W) while at Tsunza it was 1.3 m (Fig. 8 T-W).

Mangrove creek bay (Dabaso)

Water movement along the mangrove creek bay was relatively slow with a maximum current speed of 0.344 m/s and spread towards the northwest or landward (Fig. 9 A, B) while the maximum current speed across the bay was 0.24 m/s spreading towards the east or landward (Fig. 9 A, C). There was an inverse relationship when comparing V-Velocity vs U-Velocity. The maximum wave height (Hs) recorded at Dabaso over the four-day sampling period was 1.61 m (Fig. 9 D).

Relationship of depth and current

There was an observed trend of current and depth that was unique to the different sites studied. Mangrove sheltered sites like Kibokoni exhibited higher water current in the bottom waters and lower current in the surface waters. There were also observed spikes in wave height in sheltered mangrove creeks compared to open sites. In relatively open sites at Kijiweni the water current was higher in surface waters and decreased with water depth (Table 3).

Discussion

Three categories of cage site selection criteria need to be addressed for effective cage farming: physico-chemical (temperature, salinity, oxygen etc) suitable for the species under culture; oceanographic factors (waves, currents, weather, shelter, depth, substrate, winds etc); and profitability factors (legal aspects, access, land-based facilities, security, economic and social considerations). Therefore, cage design and deployment are site specific and guided by the knowledge of the site oceanographic conditions (Siddiqui and Nagarajan, 2016). A floating cage system has four main components which have distinct functions and

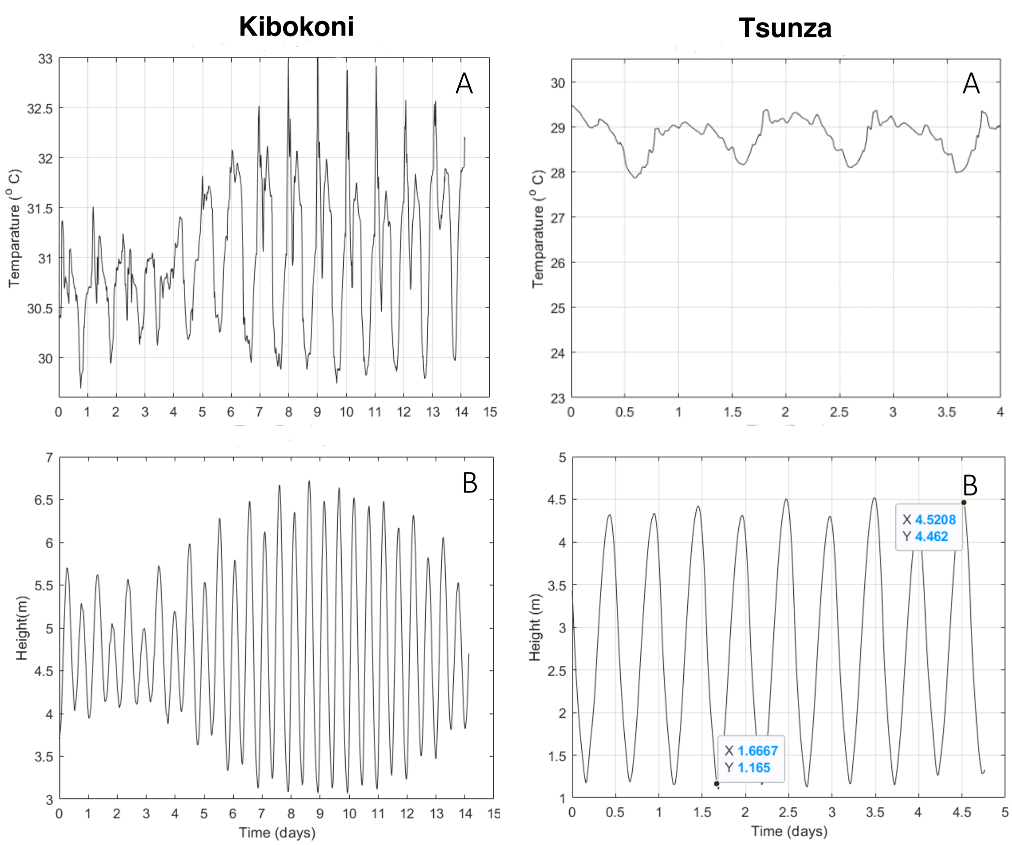

Figure 3. Temperature (A) and water column height trends (B) in two mangrove channels (Kibokoni and Tsunza) sampled at different time periods (15 and 4 days respectively).

roles: the flotilla/floating collar provides buoyancy, provides shape of the cage net and may be used as a working platform (Liu *et al.*, 2019); the cage net holds the fish that are farmed in the cage system and the netting dimensions determines the volume available for fish culture while the water exchange inside a cage is inversely proportional to the volume of the net and is influenced by the speed of the current (Piccolotti and Lovatelli, 2013); the anchors will provide the sinking effect to help bring the shape of the cage and hold it in place; while the mooring provides the connection between the sinkers and the flotilla to keep the cage in place. These aspects require understanding of the hydrodynamic characteristics that will inform the wave force acting on the cage to guide cage engineering (Kumar and Karnatak, 2014). Based on the resistance effect of cages, circular cages are more preferred since they can withstand dynamic stress and thus are

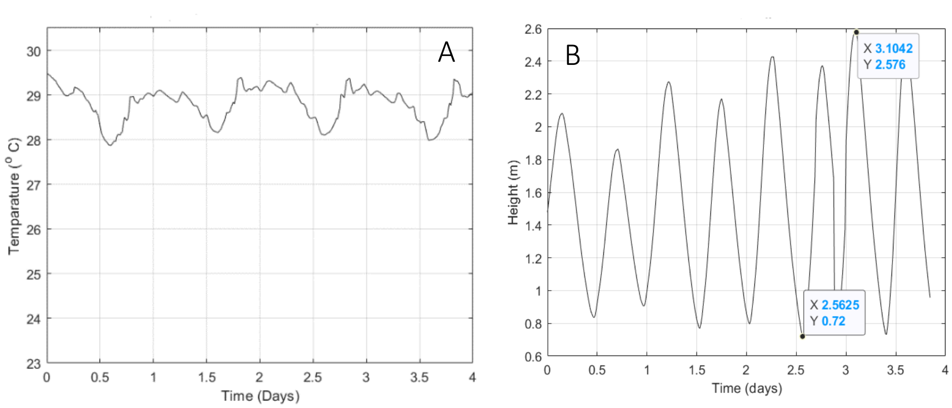

Figure 4. Changes in temperature (A) and water column height (B) over the four days experimental period at Dabaso mangrove creek bay.igure 5. Changes in U and V speed, direction and correlation between U and V velocities in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored at two different sampling points (Kijiweni 1 – B, Kijiweni 2 - A) over a 19 days sampling period.

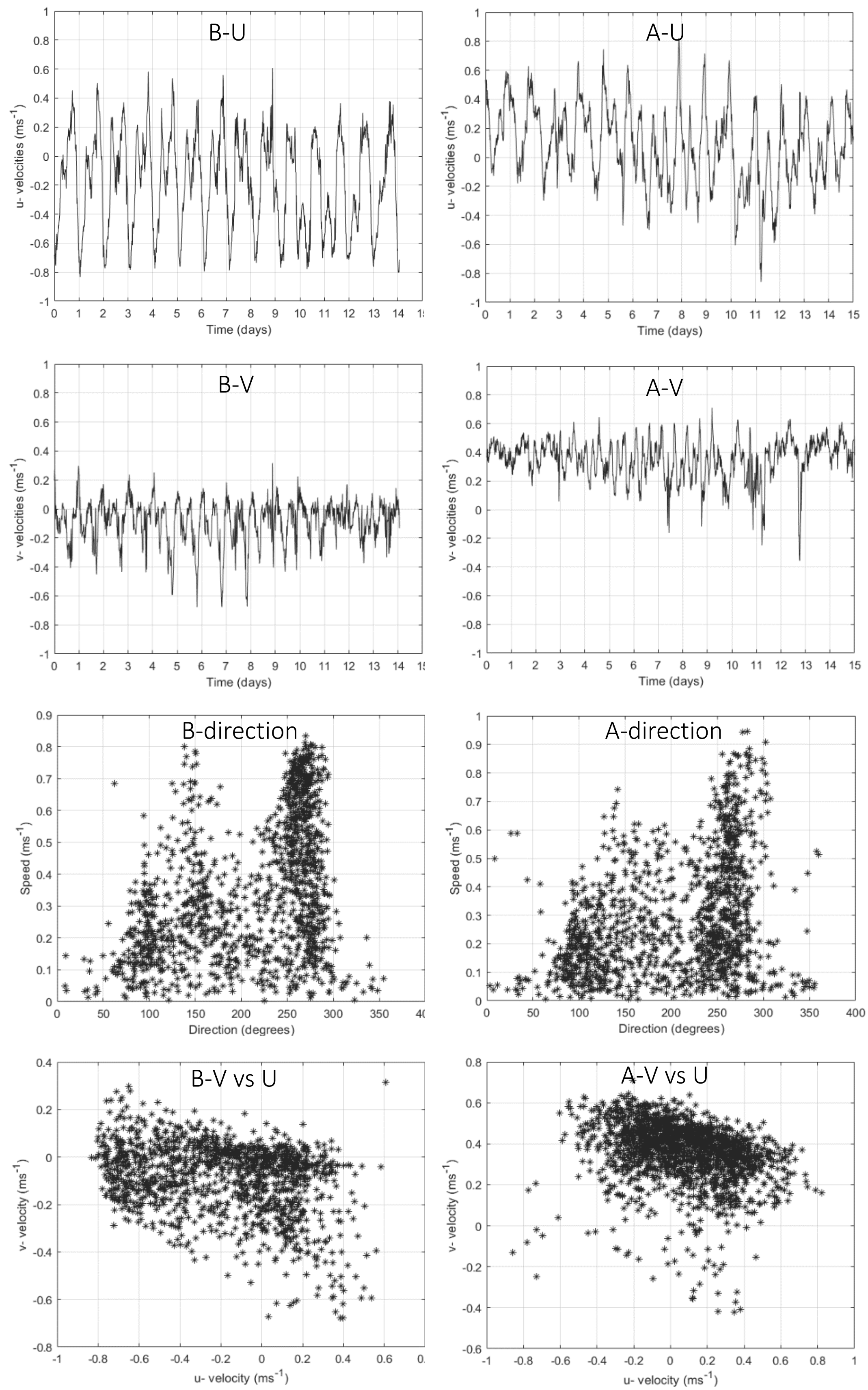

Figure 5. Changes in U and V speed, direction and correlation between U and V velocities in a relatively sheltered nearshore system at Kijiweni - south coast of Kenya monitored at two different sampling points (Kijiweni 1 – B, Kijiweni 2 - A) over a 19 days sampling period.

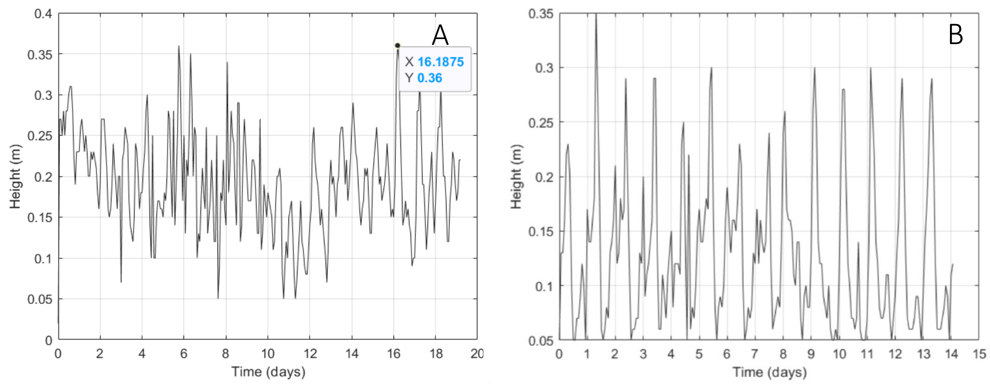

Figure 6. Variations in wave height at Kijiweni – south coast of Kenya at two different sampling points (Kijiweni 2 – A, Kijiweni 1 – B) monitored over a period of 19 days.

more suitable in less sheltered sites while square or rectangular cages will have large forces in the corners that can eventually lead to breakage and thus only suitable to sheltered sites. However, rectangular or square cages are preferable since they are easier to construct, have a higher water exchange rate within the net and can be constructed in large sizes (Piccolotti and Lovatelli, 2013).

In most coastal regions tidal currents are the predominant source of surface water currents where wave height is referred to as tidal range. This are influenced by the attractive forces, exerted by the moon and sun thus producing tidal waves during spring and neap tides with extreme long wavelengths with oscillation period of 12 h 25 min (crest and trough) being termed as high and low tides. The tidal created waves present minor problems for cage fish farms though they can create very strong tidal currents. In practice, ebb and flood tidal currents in the range 0.1–0.6 ms^{-1} and mean tidal currents of 0.03–0.2 ms^{-1} have been found to be satisfactory for good water exchange; sites where currents exceed 1ms^{-1} are not generally recommended (Braaten and Saetre 1973; Chen 1979; Chua and Teng 1980; Kerr *et al*. 1980; PPD 1986; Ikenoue and Kafuku, 1988; Rudi and Dragsund 1993; Turner, 2000). In the current study ebb and flood tidal currents in the range of 0.24 - 1.113 m/s were found at all the sites assessed. There were no sites with water currents lower than 0.1 m/s; a condition that would prevent good water exchange for oxygen supply and poor transport of faeces and excess feed, leading to a build up at the bottom of the cages creating anaerobic conditions and hydrogen sulphide in the sediments that is toxic to fish (Beveridge, 1996; Huguenin, 1997).

Areas characterized with U velocities of 1.0 – 1.5 m/s and more than 1.5 m/s are described as highly and extremely exposed respectively (Faltinsen and Shen, 2018). In one of the study sites, the along the channel current/velocity (U) recorded was higher (1.113 m/s) which could be associated with the steep topography observed in the creek (Turner, 2000). The current was above 1m/s which is problematic because of the likelihood of very large forces on the cage structure and mooring system that may lead to breakage or shifting of cages or cage deformations; this is relevant for cage design and instalments at Kibokoni mangrove channel, Kilifi Creek (Lader and Enerhaug, 2005; Huang et al., 2008; Lader *et al*., 2008; Holmer, 2010; Moe *et al*., 2010). Aarsnes *et al*. (1990) observed that up to 80 % of the expected volume available to hold fish in gravity cages may be lost in currents of 1 m/s. Current speeds of 0.13–0.35 m/s were observed to reduce the cage volume by 20–40 % by causing the cage bottom to be pushed upwards. Further, currents influence fish behaviour, affecting social hierarchies, growth and growth disparities among stock (Phillips *et al*., 1985; Leon, 1986; Jobling, *et al*. 1993; Jobling, 1995) and, reportedly, flesh quality. Also, excessive currents are associated with skeletal deformities in cage-reared carp.

The present study provides information on currents that, if well understood, will improve the marine cage resistance to dynamic stress caused by swells and currents in addition to informing suitable cage dimensions for each site. Sheltered sites with weaker currents as in the current study will require smaller cage sizes compared to exposed sites. Further, cage design will also be informed by the cost implication of making cages since the cost per cubic meter of cage volume reduces as the size increases. According to Kumar and Karnatak (2014), the cost of making a 100 m^3 cage is less compared to making two cages of each 50 m^3. Larger cages will save cost of material used to make cages and cost of management and maintaining one unit of cage compared to separate small cages even

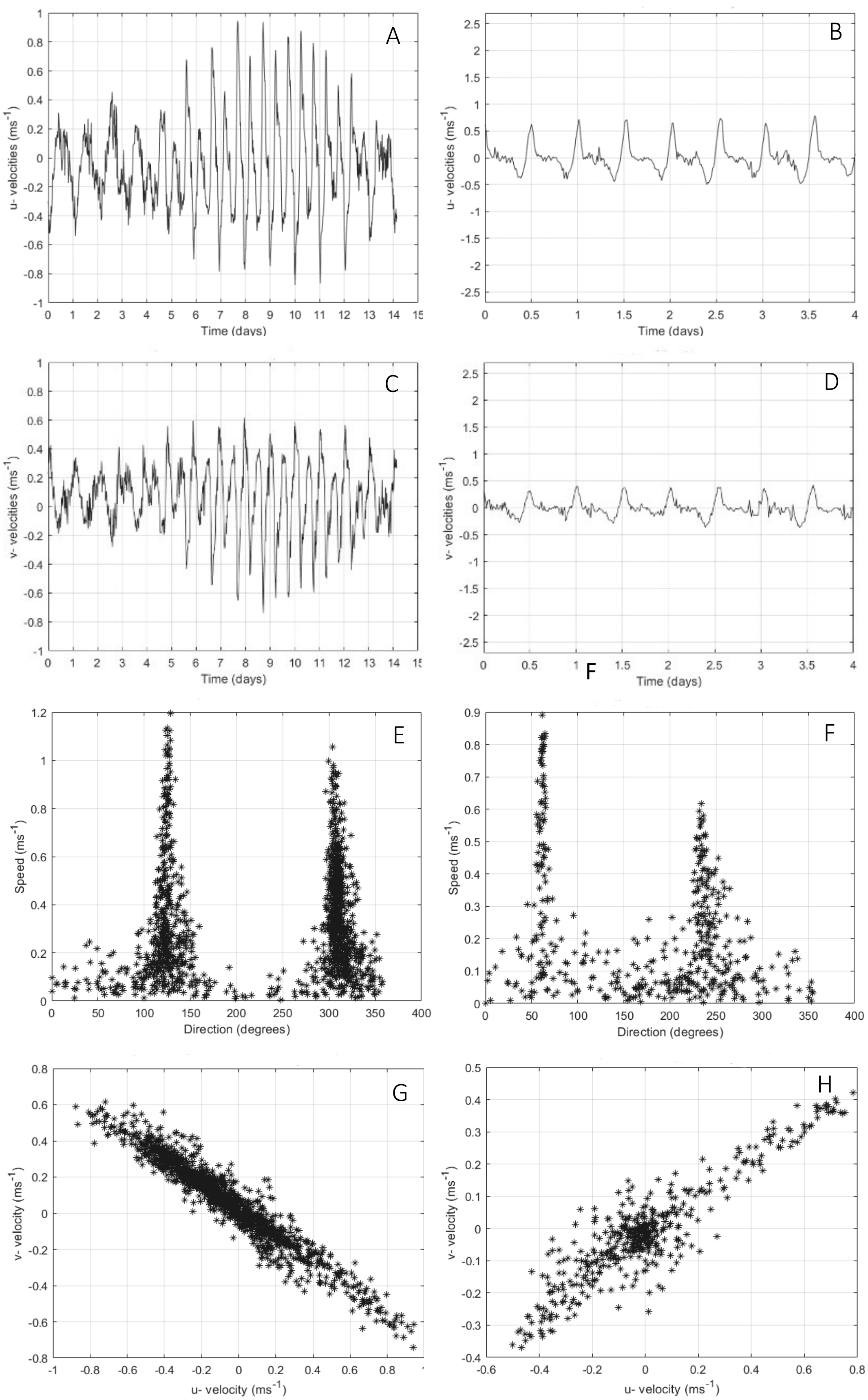

Figure 7. Changes in U and V velocity, direction and relationship between U and V velocities in the mangrove channels of Kibokoni (Kilifi creek – A, C, E, G) and Tsunza (Mwache creek- B, D, F, H) in Kenya monitored at different time periods.

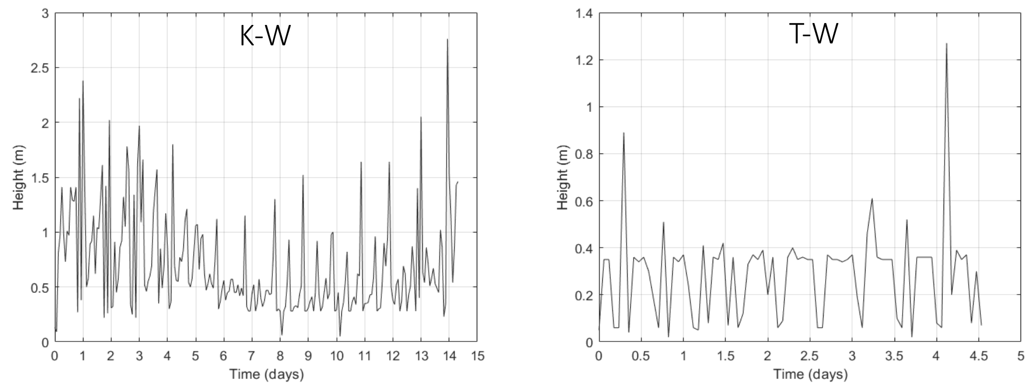

Figure 8. Variations in significant wave height at Kibokoni (K-W) and Tsunza (T-W) monitored over 14 days and 4 days respectively.

though the losses could be huge in the event of torn nets or replacements (Piccolotti and Lovatelli, 2013). Also, in smaller cages the stocking density may be increased (200 kg/m^3) compared to bigger cages (25 kg/m^3), but smaller cages could lead to bigger losses of feed which is pushed quickly out of the cage by currents before consumption by fish. For these reasons currents are important in cage site selection and design (Piccolotti and Lovatelli, 2013).

Wind is the main ingredient in the formation of waves in the open ocean which are the greatest determinant of site selection in cage farming. When winds blow across water, a drag is applied on the surface and pushes the water up, creating a wave. The height will increase as long as the wind is strong enough to add energy to the wave. Once a wave is generated, it will travel in the same direction until it meets land or is dampened by an opposing force such as winds blowing against it in the opposite direction, or by friction (Bascom, 1964). The height of wind-created waves depends on the wind velocity, the duration of the wind, the fetch length (distance where wave development can take place) and the presence of other waves when the wind begins to blow. The current study recorded wave heights of between 0.35 and 2.7 m in the four sites assessed which are within the mean wave height recommendations of other studies (Beveridge, 1996; Huguenin, 1997; Aguilar-Manjarrez *et al*, 2013). The site with the highest wave height is a mangrove creek which by its nature is well sheltered though the steep bathymetry of the creek might be associated with the attained wave height. According to Faltinsen and Shen (2018), wave heights of more than 2.0-3.0 m and more than 3.0 m are found in areas described as highly and extremely exposed, respectively. Significant wave heights of 2 m are most suitable for cage farm sites since cages can tolerate such heights. However, it is advisable to construct cages that can tolerate significant wave heights of 4 – 5 m. Some ocean cages may be constructed to tolerate significant wave heights of 7 - 8 m but in such cases there is need for special considerations of how such cages can be operated before selecting such sites. Such extreme wave heights were not recorded in the current study. Cage farms set in areas with high wave heights are difficult and expensive to operate since operational access is reduced and thus not an option for small scale fish farmers since they can only be operated with large and expensive boats. Therefore, knowledge of the wave climate of an area helps in choosing the correct cage technology and mooring system that will ensure integrity of the cage (Cairns and Linfoot, 1990; Pérez *et al*., 2003).

Tidal heights significantly influence movement of cages and the recommended heights are between 2-3 m (Francesco Cardia *et al*, 2015). Tidal ranges of 1.67 m have been observed to influence movement of 22 m diameter circular cages by 10.1 and 7.7 m east and north thus increasing the effective area under the cage available for fish waste deposition by 72 % (Corner *et al*., 2006). The current study established a tidal height range of between 1.87 and 4.0 m in all assessed sites. This is suitable for cage drainage although it may lead to significant cage movements that require adjustments to the mooring system to avoid cage breakage. To mitigate against breakage and compensate for movement, rectangular cages are normally oriented with the larger dimension placed in the streamwise direction. However, with this configuration, circulation of flows around and through the entire farm becomes complex since cages downstream may experience reduced water exchange compared to the upstream cages leading to more wastes, decrease in quality of water and dissolved oxygen (Kleberta *et al*., 2013).

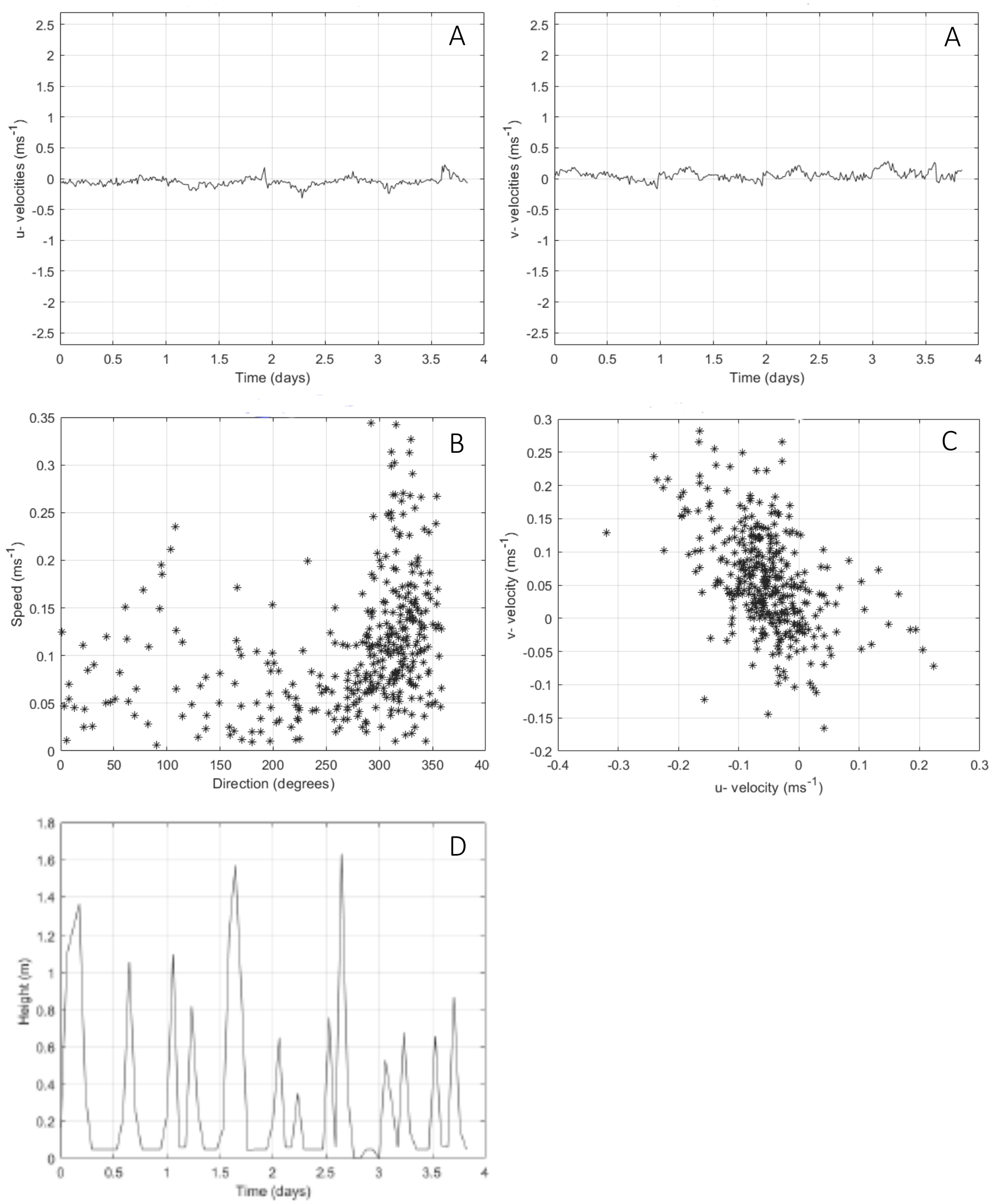

Figure 9. Changes in U and V velocity (A), direction (B) and correlation between U and V velocities (C) and significant wave height (D) at Dabaso mangrove creek bay monitored over a period of four days.

According to Li (1994), a cage should be held within the plankton- rich surface (< 2 m) waters. Very shallow cages (< 1.5 m) have been shown to affect body shape and retard growth in carp and tilapia farms (Maruyama and Ishida, 1976, 1977) although some other fish like flatfish (turbot and halibut) may prefer shallow cage depths of 0.9 – 1.6 m (Kerr *et al.*, 1980; Martinez Cordero *et al.*, 1994). In the current study varied water depth was found at low tides (ebb water) for different sites ranging from 2.0 – 12 m depending on the characteristics of the site. Taking cognizance of the fact that a cage needs to operate between 0.9 – 2 m from the water surface based on culture species, the sites assessed are suitable for cage farming though species selection needs to be undertaken based on the specific requirements. Equally, the depth of a cage site is a determinant of the mooring system to be used. Usually water depths with a distance of 2 – 5 m from the bottom of the cage to the sea bottom is recommended if the current conditions are suitable (Beveridge, 1996; Huguenin, 1997). Depths above 100 m will greatly increase the costs of the mooring system since long mooring lines will be needed.

Cages should be sited in sufficient depth to maximize the exchange of water yet keep the cage bottoms well clear of the substrate. Indeed, water is drawn into the cage not only through the sides but also through the bottom and therefore, as the cage bottom approaches the substrate, water flow is impeded thus the requirement to hold fish at least 4 – 5 m above the sediments (Chacon Torres *et al*., 1988).

The current study established an increment of water current with depth in sheltered mangrove channels that were associated to tidal currents, while in relatively open sites surface waters had stronger currents than bottom waters. The study provides new information for consideration when developing cages in mangrove channels that are assumed to be sheltered and thus less influenced by currents. Establishment of the bottom topography/bathymetry is also important as it gives information of sloping contours that will inform placement of anchors and distance of cage placement from the bottom (Turner, 2000). Depth estimations need to be well compensated with tidal fluctuations which may range from 0.5 m to over 10 m depending on the part of the world and calmness of the weather (Muir Wood and Fleming, 1981).

Conclusion and recommendations

The hydrodynamic characteristics of the different sites studied on the north and south coast of Kenya indicate that Kenyan waters are suitable for cage culture. Based on the findings, different cage designs need to be employed in each site to meet the varied dynamics in currents, waves, tidal heights, depth, flow and temperatures. Being a new potential area for cage culture in the region, more studies are required to characterize the entire nearshore coastal area to inform development of the industry in addition to provision of data for suitable species for culture and contribute to marine spatial planning to minimise user conflicts.

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References

Aarnses J, Rudi H, Loland, G (1990) Current forces on cage, net deflection. Engineering for offshore fish farming. Thomas Telford, New York. pp 137-152

Abreu MH, Varela DA, Henriquez L, Villarroel A, Yarish C, Sousa-Pinto I, Buschmann AH (2009) Traditional vs. integrated multi-trophic aquaculture of *Gracilaria chilensis*. Aquaculture 293: 211-220

Aguilar-Manjarrez J, Lovatelli A, Soto D (2013) Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges. FAO book series [DO - 10.13140/RG.2.1.2989.1927]

Balarin JD (1985) National reviews for aquaculture development in Africa. 7. Kenya. FAO Fisheries Circular (770.7). 96 pp

Bao-Tong H (1994) Cage culture development and its role in aquaculture in China. Aquaculture Research 25: 305-310

Bascom W (1964) Waves and beaches. Anchor Books, New York. 267 pp

Beveridge M (1996) Cage aquaculture. Fishing News Books. Blackwell Scientific. 346 pp

Beveridge CM (2004) Cage aquaculture, third edition. Blackwell Publishing. Library of Congress. 380 pp [ISBN 1-4051-0842-8]

Braaten BR, Saetre R (1973) Rearing of Salmonids in Norwegian coastal waters – Environment and types of installations. Translation Series of the Fisheries Research Board of Canada 2759. Fisheries Research Board of Canada, Ottawa. 319 pp

Cairns J, Linfoot BT (1990) Some considerations in the structural engineering of sea-cages for aquaculture. Engineering for offshore fish farming. Thomas Telford. pp 63-77

Campbell BM, Vermeulen SJ, Aggarwal PK, Corner-Dolloff C, Girvetz E, Loboguerrero AM, Ramirez-Villegas J, Rosenstock T, Sebastian L, Thornton P, Wollenberg E (2016) Reducing risks to food security from climate change. Global Food Security (2016) [http: //dx.doi.org/10.1016/j.gfs.2016.06.002i]

Chacon Torres A, Ross LG, Beveridge MCM (1988) The effects of fish behaviour on dye dispersion and water exchange in small net cages. Aquaculture 73: 283-293

Chen F-Y (1979) Progress and problems of net cage culture of grouper (*Epinephelus tauvina*) in Singapore. Proceedings of the Annual Meeting of the World Mariculture Society 10: 260-71

Chen J, Guang C, Xu H (2007) A review of cage and pen aquaculture: China. FAO Fish Technical Paper 498. 53 pp

Chua T-E, Teng SK (1980) Economic production of estuary grouper *Epinephelus salmoides* Maxwell, reared in floating cages. Aquaculture 20: 187-228

Colbourne JHDB, Allen (2001) Observations on motions and loads in aquaculture cages from full scale and model scale measurements. Aquaculture Engineering 24 (2): 129-148

Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B, Twomlow S (2008) Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? Agriculture, Ecosystems and Environment 126: 24-35 doi:10.1016/j.agee.2008.01.007

Corner RA, Brooker AJ, Telfer TC, Ross LG (2006) A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites. Aquaculture 258: 299-311

Cranford PJ, Duarte P, Robinson S, Fernández-Reiriz MJ, Labarta U (2014) Suspended particulate matter depletion and flow modification inside mussel (*Mytilus galloprovincialis*) culture rafts in the Ría de Betanzos, Spain. Journal of Experimental Marine Biology and Ecology 452: 70-81

Dronkers JJ (1964) Tidal computations in rivers and coastal waters. North Holland publishing company. 518 pp [ISBN-13 : 978-0720416121]

Faltinsen OM, Shen Y(2018) Wave and current effects on floating fish farms. Journal of Marine Science and Application 17 (3): 284-296 [https://doi.org/10.1007/s11804-018-0033-5]

FAO (1977) Establishment of a pilot project for coastal aquaculture in Kenya. Report of a mission to plan a pilot farm. Feb – March 1977. FAO, Rome. ADCP/MR/77/2. 11 pp

FAO (2018) The FAO blue growth initiative: Strategy for the development of fisheries and aquaculture in Eastern Africa. Menezes A, Bartley D, Metzner R, Ansah Y. FAO Fisheries and Aquaculture Circular No. 1161, Rome, Italy. 65 pp

FAO (2020) The state of world fisheries and aquaculture. Sustainability in action. Food and Agriculture Organization of the United Nations. 224 pp

Fredheim A, Langan R (2009) Advances in technology for offshore and open ocean finfish aquaculture. In: Burnell G, Allan G (eds) New technologies in aquaculture. Sawston: Woodhead Publishing Series in Food Science, Technology and Nutrition (2009): 914-944

Findlay RH, Watling L, Mayer LM (1995) Environmental impact of salmon net-pen culture on marine benthic communities in Maine—a case study. Estuaries 18: 145-179

Francesco Cardia AL (2015) Aquaculture operations in floating HDPE cages. Rome. 176 pp

Gignoux H, Messier RH (1999) Computational modelling for finfish aquaculture net pens. Ocean Engineering International 3 (1): 12-22

Golden CD, Allison EH, Cheung WWL, Dey MM, Halpern BS, McCauley DJ, Smith M, Vaitla B, Zeller D, Myers SS (2016) Nutrition: Fall in fish catch threatens human health. Nature 534: 317-320 [https://doi.org/10.1038/534317a]

Grant J, Bacher CA (2001) A numerical model of flow modification induced by suspended aquaculture in a Chinese Bay. Canadian Journal of Fisheries and Aquatic Science 58: 1003-1011

Halpern BS, Frazier M, Afflerbach J, Lowndes JS, Micheli F, O'Hara C, Scarborough C, Selkoe KA (2019) Recent pace of change in human impact on the world's ocean. Science Report 9: 11609 [https://doi.org/10.1038/s41598-019-47201-9]

Holmer M, Kristensen E (1994) Organic matter mineralisation in an organic-rich sediment: Experimental stimulation of sulphate reduction by fish food pellets. Microbiology Ecology. 14: 33-44

Holmer M (2010) Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. Aquaculture Environment Interaction: 57-70

Huang C-C, Tang H-J, Liu J-Y (2008) Effects of waves and currents on gravity-type cages in the open sea. Aquacultural Engineering 38: 105-116

Huguenin JE (1997) The design, operations and economics of cage culture systems. Aquacultural Engineering 16: 167-203

Ikenoue H, Kafuku T (1988) Modern methods of aquaculture in Japan, 2nd edition. Elsevier, Amsterdam. 274 pp

IPCC (2007) Quatrième rapport d'évaluation, bilan 2007 des changements climatiques – disponible enligne [http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf]

Jiddawi NS, Ohman MC (2002) Marine fisheries in Tanzania. AMBIO 31: 518-527

Jobling M, Baardvik BM, Christiansen JS, Jørgensen EH (1993) The effects of prolonged exercise training on growth performance and production parameters in fish. Aquaculture International 1: 95-111

Jobling M (1995) Simple indices for the assessment of the influences of social environment on growth performance, exemplified by studies on Arctic charr. Aquaculture International 3: 60-5

Karakassis I, Tsapakis M, Hatziyanni E, Papadopoulou KN (2000) Impact of cage farming of fish on the seabed of three Mediterranean coastal areas. ICES Journal of Marine Science 57: 1462-1471

Kaunda-Arara B, Rose GA, Muchiri S, Kaka R (2003) Long-term trends in coral reef fish yields and exploitation rates of commercial species from coastal Kenya. Western Indian Ocean Journal of Marine Science 2: 105-116

Kawakami T (1964) The theory of designing and testing fishing nets in model. In: Kristjansson H (ed) Modern fishing gear of the world, Vol. 2. Fishing News Books, Oxford. pp 471-482

Kerr NM, Gillespie MJ, Hull ST, Kingwell S (1980) The design construction and location of marine floating cages. In: Proceedings of the Institute of Fisheries Management Cage Fish Rearing Symposium, 26-27 March 1980. University of Reading. Janssen Services, London. pp 23-49

Klebert P, Lader P, Gansel L, Oppedal F (2013) Hydrodynamic interactions on net panel and aquaculture fish cages: A review. Ocean Engineering 58: 260-274

Kumar V, Karnatak G (2014) Engineering consideration for cage aquaculture. IOSR Journal of Engineering (IOSRJEN) 4 (6): 1-18 [www.iosrjen.org\]

Lader PF, Enerhaug B (2005) Experimental investigation of forces and geometry of a net cage in uniform flow. IEEE Journal of Ocean Engineering 30: 79-84

Lader P, Dempster T, Fredheim A, Jensen Ø (2008) Current induced net deformations in full-scale cages for Atlantic salmon (*Salmo salar*). Aquaculture Engineering 38: 52-65

Leon KA (1986) Effect of exercise on feed consumption, growth, food conversion and stamina of brood trout. The Progressive Fish-Culturist 48: 43-46

Li SF (1994) Fish culture in cages and pens. In: Li S, Mathias J (eds) Freshwater fish culture in China: Principles and practice. Elsevier, Amsterdam. pp 305-46

Linden O, Lundin CG (eds) (1996) Proceedings of national workshop on Integrated Coastal Zone Management in Tanzania. May 8-12. The World Bank Land,

Water and Natural Habitats Division, Environmental Department. 166 pp

Liu H-Y, Huang X-H, Wang S-M, Hu Y, Yuan T-P, Guo G-X (2019) Evaluation of the structural strength and failure for floating collar of a single-point mooring fish cage based on finite element method. Aquacultural Engineering 85: 32-48

Martinez Cordero FJ, Beveridge MCM, Muir JF, Mitchell D, Gillespie M (1994) A note on the behaviour of adult Atlantic halibut, *Hippoglossus hippoglossus* (L.), in cages. Aquaculture and Fisheries Management 25: 475-81

Maruyama T, Ishida R (1976) Effect of water depth in net cages on the growth and body shape of *Tilapia mossambica*. Bulletin of the Freshwater Fisheries Research Laboratory of Tokyo 26: 11-19

Maruyama T, Ishida R (1977) Effects of water depth on the growth and body shape of common carp raised in net cages. Bulletin of the Freshwater Fisheries Research Laboratory of Tokyo 27: 95-102

McClanahan TR, Hicks C, Darling E (2008) Malthusian overfishing and efforts to overcome it on Kenyan coral reefs. Ecological Applications 18 (6): 1516-1529

McManus JW, Reyes RB JR, Nanola CL JR (1997) Effects of some destructive fishing methods on coral cover and potential rates of recovery. Environmental Management 21 (1): 69-78

Milne PH (1972) Fish and shellfish farming in coastal waters. Fishing News (Books), London. 208 pp

Mirera HOD (2011) Experimental polyculture of milkfish (*Chanos chanos*) and Mullet (*Mugil cephalus*) using earthen ponds in Kenya. Western Indian Ocean Journal of Marine Science 10 (1): 59-71

Mirera OD, Ochiewo J, Munyi F, Muriuki T (2013) Heredity or traditional knowledge: Fishing tactics and dynamics of artisanal mangrove crab (*Scylla serrata*) fishery. Ocean and Coastal Management 84: 119-129

Mirera OD (2019) Small scale milkfish (*Chanos chanos*) farming in Kenya: An overview of the trend and dynamics of production. Western Indian Ocean Journal of Marine Science 18 (2): 11-24

Mirera OD, Kimathi A, Ngarari MM, Magondu EW, Wainaina M, Ototo A (2020) Societal and environmental impacts of seaweed farming in relation to rural development: The case of Kibuyuni village, south coast, Kenya. Ocean and Coastal Management 194: 105253

Mmochi AJ (2015) Community based milkfishfFarming in Tanzania. Western Indian Ocean Journal of Marine Science 15: 99-103

Moe H, Fredheim A, Hopperstad OS (2010) Structural analysis of aquaculture net cages in current. Journal of Fluids and Structures 26: 503-516

Muir Wood AM, Fleming CA (1981) Coastal hydraulics, 2nd edition. Macmillan, London. 280 pp

Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP, Halling C, Shpigel M, Yarish C (2004) Integrated aquaculture: rationale, evolution, and state of the art emphasizing on seaweed bio filtration in modern mariculture. Aquaculture 231: 361-391 [https://doi.org/10.1016/j.aquaculture.2003.11.015]

O'Donncha F, Hartnett M, Nash S (2013) Physical and numerical investigation of the hydrodynamic implications of aquaculture farms. Aquaculture Engineering 52: 14-26

Österblom H, Folke C (2013) Emergence of global adaptive governance for stewardship of regional marine resources. Ecology and Society 18 (2): 4 [http://dx.doi.org/10.5751/es-05373-180204]

Pauly D, Alder J, Bennett E, Christensen V, Tyedmers P, Watson R (2003) The future for fisheries. Science 302 [www.sciencemag.org]

Pérez OM, Telfer TC, Ross LG (2003) On the calculation of wave climate for offshore cage culture site selection: a case study in Tenerife (Canary Islands). Aquacultural Engineering 29: 1-21

Petrell RJ, Alie SY (1996) Integrated cultivation of salmonids and seaweeds in open systems. Hydrobiologia 326-7: 67-73

Phillips MJ, Beveridge MCM, Ross LG (1985) The environmental impact of salmonid cage culture on inland fisheries: present status and future trends. Journal of Fish Biology 27 (Suppl. A): 123-137

Piccolotti F, Lovatelli A (2013) Construction and installation of hexagonal wooden cages for fish farming: A technical manual. FAO Fisheries and Aquaculture Technical Paper 576. 90 pp

PPD (1986) Manual on floating netcage fish farming in Singapore's coastal waters. Fisheries Handbook, Primary Production Department, Singapore. 17 pp

Rudi H, Dragsund E (1993) Localization strategies. In: Reinertsen H, Dahle LA, Jørgensen L, Tvinnereim K (eds) Fish farming technology. AABalkema, Rotterdam. pp 169-176

Shi J, Wei H, Zhao L, Yuan Y, Fang J, Zhang J (2011) A physical–biological coupled aquaculture model for a suspended aquaculture area of China. Aquaculture 318: 412-424

Siddiqui MA, Nagarajan V (2016) Dynamics of a single point mooring marine aquaculture cage as a simple vibrating system. International Journal of Maritime Technology (IJMT) 5: 13-25

Stokes CJ, Howden M (2010) Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future. CSIRO Publishing, Collingwood. 280 pp

Tilseth S, Hansen T, Møller D (1991) Historical development of salmon culture. Aquaculture 98: 1-9

Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang JG (2009) Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297: 1-9

Troell M, Hecht T, Beveridge M, Stead S, Bryceson I, Kautsky N, Mmochi A, Ollevier F (eds) (2011) Mariculture in the WIO region – challenges and prospects. WIOMSA Book Series No. 11. viii+59 pp

Turner R (2000) Offshore mariculture: site evaluation. In: Muir JF, Basurco B (eds) Mediterranean offshore mariculture. Options Méditerranéennes, Series B, No. 30. CIHEAM, Zaragoza. pp 141-57

UN Nutrition (2021) The role of aquatic foods in sustainable healthy diets. United Nations. 57 pp [https://www.unnutrition.org/wp-content/uploads/FINAL-UN-Nutrition-Aquatic-foods-Paper_EN_.pdf]

Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, Jackson JBC, Lotze HK, Micheli F, Palumbi SR, Sala E, Selkoe KA, Stachowicz JJ, Watson R (2006) Impacts of biodiversity loss on ocean ecosystem services. Science 314: 789-790

Wu RSS (1995) The environmental impact of marine fish culture; towards a sustainable future. Marine Pollution Bulletin 31: 159-166