

Implications of an extensive saltwater barrage on the distribution of black clam in a tropical estuarine system, Southwest coast of India

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Abstract

Based on a monthly field sampling over a year in the Kochi backwaters (KBW), this study presents the larval ecology of black clam and discusses how an extensive saltwater barrage [Thannermukkom barrage (TB)] impacted the natural black clam resource distribution. Spatial variations in salinity were found minimal during the Southwest Monsoon (June-September) due to the predominance of the freshwater associated with heavy monsoonal rainfall. Conversely, significant spatial changes in salinity were evident during the Pre-Southwest Monsoon (March-May) and Post-Southwest Monsoon (October - February). Monthly sampling exercises revealed that the black clam stock in the KBW breeds throughout the year, as their larvae were found (8 No.m⁻³ to 494 No.m⁻³) in all the locations. This observation is the modification of the traditional belief that black clam in the KBW breeds only twice a year. Mesohaline condition (salinity 5-18) is the most conducive for peak spawning and larval production. There was two peak larval production times in the KBW over a year, mainly associated with the prevalence of the optimum salinity conditions on different spatial scales. The closing of the TB after the Southwest Monsoon (September) causes shrinkage of the area of the oligohaline and mesohaline conditions, the most conducive environment for the peak spawning and larval production of black clam in the KBW. This study presents a clear case of how human alterations of the natural environment impact valuable biological resources, which may apply to many similar aquatic ecosystems across the globe.

Keywords: Black clam; Larvae, spawning; saltwater barrage; KBW.

1. Introduction

The annual landing of clam resources in the Kerala State of India is about 66,000 tons, of which black clam (*Villorita cyprinoides*) contributes two-third of the total production (CMFRI, 2009; Suja and Mohamed, 2010). Black clam is harvested mostly (>75%) from the clam beds of the Kochi backwaters (KBW) in the southern Vembanad section through the involvement of ~ 4,000 fisherman families (Gopal et al., 2014; Suja and Mohamed, 2010). Black clam meat is a cheap source of protein, and their shells are used as a raw material for lime and cement production. Besides their fishery potential, black clams are used as bio-indicators in pollution monitoring studies due to their wide distribution, reasonable size, easy sampling and longer life span (Arun, 2005; George et al., 2013; Sujatha et al., 1996). Black clam produces a large number of planktonic larvae (meroplankton), which spend several weeks in the water column before they settle in the bottom substratum (Achary, 1988). Meroplanktonic life black clams are more sensitive to surrounding environmental features compared to their adult life stages (Piontkovski et al., 2006; Richardson, 2008), and therefore, any significant ecological changes can easily alter their development, survival and settlement. The survival and developmental impairments among the meroplankton larvae would negatively impact black clam fishery in the natural environment (Ziadi et al., 2015).

KBW is the most extensive estuarine system along the west coast of India. The physicochemical parameters in this backwater system change spatially and seasonally, especially changes in the tide at one end and river influx at the other (Balachandran et al., 2008; Jyothibabu et al., 2006; Madhu et al., 2007; Madhupratap, 1987; Qasim, 2003). The KBW in its southern (Vembanad) region is separated into brackish and nearly freshwater environments by the Thannermukkom barrage (TB) (Figure 1). TB was constructed in 1974 and is functional since 1976. It is about 2 km long, situated across the KBW, and its shutters are closed during December - May period to prevent saltwater entry further south of TB where paddy (rice) fields are dominant. The closure of TB diminishes the tidal inflow into the Vembanad section of the KBW. The barrier inhibits the free flow and mixing of water between its either sides, severely altering the natural flushing characteristics of the system, causing negative impacts on the ecology (ecological backlash) of the KBW (Anon, 2001; Arunpandi et al., 2020a,b,c).

Past studies on black clam in the KBW mainly present their biology, occurrence, distribution and utilisation aspects (Arun, 2005; Lakshmanan and Nambisan, 1983; Laxmilatha and Alloyicious, 2001; Laxmilatha and Appukuttan, 2002; Narasimham et al., 1993; Ravindran et al., 2006; Sathiadhas and Hasan, 2004; Vinu Chandran, 2002). Some of these studies indicate that black clam attains sexual maturity when they reach an 11-15cm size, spawns twice in a year, tolerates specific salinity changes (0-10 units) and black clam beds in the KBW negatively impacted in recent times due to the TB. However, a thorough quantitative analysis of spatiotemporal variations in hydrography in the KBW to scientifically

conclude the above supposition is unavailable so far. The formation of black clam beds depends mainly on successful spat settlement, which in turn, is the result of the prevailing hydrographical conditions. Being a sizeable monsoonal estuary, the hydrographical settings in the KBW vary widely, and such spatial and temporal changes in hydrographical conditions could alter the distribution of planktonic organisms (Arunpandi et al., 2020a,c; Haridevan et al., 2015; Jyothibabu et al., 2006; Madhu et al., 2007). The larval stage of black clam is meroplanktonic, and their quantification in an environment provides a valuable clue on the location of black clam beds in an aquatic environment (Gosling, 2003). The body size of the black clam larvae usually varies from 55 - 140 μ m (Achary, 1988) and hence, misses out from accounting in usual mesoplankton sample collection using traditional plankton nets with mesh size 200 or 300 μ m. Therefore, here in this study, we used a customised plankton net with 50 μ m mesh size for black clam larval collection. Under this study on black clam in the KBW, we considered the following two significant objectives (a) to understand the ecology of black clam larval dispersal and (b) to infer how TB alters the black clam resource distribution in the KBW.

2. Materials and methods

2.1. Study area and sampling

The KBW (9° 40' to 10°12' N and 76°10' to 76°30' E) is the largest monsoonal estuary along the southwest coast of India. Salinity incursion dominates the KBW during the non-rainy (Pre-Southwest Monsoon and Post-Southwest Monsoon) periods. The annual rainfall in the Kochi estuary is about 3.2 m, of which >70% occurs during the SWM (last week of May to September). During the SWM period, KBW receives an enormous quantity of freshwater discharge from six rivers. With the onset of the SWM, the hydrographic conditions in the KBW undergo drastic changes due to the massive influx of freshwater, transforms like a freshwater lake. During this period, the salinity incursion is restricted only to the inlet (barmouth) region (Jyothibabu et al. 2008, Arunpandi et al., 2020a,b,c). TB (Figure 1), when it is closed, separates KBW into sections of vast brackish water in its north and freshwater in its south. The hydraulic shutters of TB remain closed during December - May period to stop the saline water intrusion into the paddy fields located south of the barrage. Monthly field sampling was carried out in three locations over a year from January- December 2015 period (except April-there was no sampling). The study locations were selected along the salinity gradients; two locations were chosen north of the TB while one was to the south of it (Figure 1). Station 1 (Thevara) was located near Barmouth in the downstream region, with an average depth of about 8m. Station 2 (Murinjapuzha) was located in the midstream with a depth of 3m. This location was 14km south of station 1 and 13km north of TB. Station 3 in Muhamma represented the upstream region and was located 8km south of the barrage with a depth of 5m (Figure 1). These study locations in the KBW were grouped into different salinity levels following McLusky, (1993) viz.,

polyhaline (salinity 18-30), mesohaline (salinity 5-18), oligohaline (salinity 0.5-5), and limnohaline (salinity < 0.5).

2.2. Sampling methods

Salinity and temperature were measured using a CTD profiler (Seabird- SBE 19plus V2). A turbidity meter (Eutech TN-100) was used to measure the surface and subsurface (2m) turbidity. Water samples for nutrients and dissolved oxygen were collected from the surface and subsurface layers using the 5L Niskin sampler (Hydrobios-Kiel). Dissolved oxygen was measured based on Winkler's method. The analyses of macronutrients (silicate, nitrate and phosphate) were carried out based on the standard procedure (Grasshoff et al., 1983). The total phytoplankton biomass (chlorophyll *a*) was measured from water samples (1 litre) filtered through 0.2 µm filter papers. These filter papers with phytoplankton cells were extracted using 10 ml 90% acetone to obtain chlorophyll *a* (Chl-*a*), which was measured using a Trilogy fluorometer (Turner Designs, USA) following the standard procedure (UNESCO, 1994). The size-based phytoplankton biomass (size-fractionated Chl-*a*) was quantified based on a standard system (Arunpandi et al., 2017; Jyothibabu et al., 2013). One litre of the water samples was passed through the different meshes and concentrated in different-sized filters papers (step-wise filtration) based on the standard procedure. The size-based phytoplankton thus separated on filters were then estimated for Chl-*a* to quantify the biomass present in different phytoplankton sized fractions.

Black clam larval distribution was quantified based on plankton samples collected by horizontal hauls of 50µm customised plankton net (mouth diameter 30cm). A digital flow meter was attached across the mouth of the net to estimate the volume of water filtered through the net. The clogging of the net was avoided by limiting the hauling time to 3-5 minute. The plankton samples collected were preserved in 4 % formalin. In the laboratory, the samples were divided into two using Folsom splitter; one half was used for the quantification of the black clam larvae, and the other half for their size measurements (Achary, 1988). Various life stages of the black clam larvae were counted, and their abundance was represented in unit volume (No.m⁻³). The larval body size was measured by randomly considering 50-100 specimens from each larval category (egg, trochophore/veliger and pediveliger), and their shell length was measured in an inverted microscope equipped with an image analyser (Model No: Olympus 1X 51). In this study, we quantified the total abundance of black clam larvae as well as the abundance of three different life stages: eggs, veliger/trochophore (because of trochophore larva metamorphoses into veliger within a short period (6-12hrs) and pediveliger, based on their morphology).

2.3. Statistical analysis

2.3.1. Redundancy analysis (RDA)

The interrelationships within and between the environment and the biological parameters (black clam larval abundance and Chl-*a*) were analysed using RDA (CANOCO 4.5). Initially, the data was tested with Detrended Correspondence Analysis (DCA) for finding a suitable ordination technique. DCA results showed axis gradient length < 2 , suggesting linear multivariate RDA as the most appropriate method for the present data set (Leps and Smilauer, 2003). The biological variables were log-transformed before the analysis. The ordination significance was tested with Monte Carlo permutation tests (499 unrestricted permutations) ($p < 0.05$). The results of RDA was presented in Triplots in which points represent sampling months; biological and environmental variables were shown by arrows; salinity was denoted with a dotted pink colour line. Spatial and seasonal changes in the environmental parameters and the black clam larval abundance were tested with ANOVA. Primarily, datasets were tested for their distribution and homogeneity. For those with normal distribution, parametric ANOVA was performed, whereas, non-parametric ANOVA was used for the other case (Kruskal-Wallis). The normality test, Parametric ANOVA and Non- Parametric ANOVA were performed in the XL-Stat Pro software package.

3. Results

3.1. Environmental parameters

3.1.1. Temperature, salinity and turbidity

Salinity showed significant spatial as well as temporal differences ($P < 0.05$, Table 1). The maximum rainfall in the study area was from June to October (Supplementary material 1). Seasonally, salinity ranged from oligohaline to polyhaline (0.5 to 29.1 in surface and 0.5 to 29.6 in the subsurface) in the downstream region, limnohaline to mesohaline (0.05 to 12.63 in surface and 0.05 to 15.6 in the subsurface) in mid-and limnohaline to oligohaline (0.04 to 3.93 in surface and 0.04 to 3.94 in the subsurface) in the upstream region. Regardless of the locations, salinity was higher during the December - March period, as compared to other sampling periods. In the downstream, salinity was polyhaline/euhaline levels during the period between January and March while it becomes oligohaline/limnohaline levels during May to June period. Subsequently, salinity was found to be < 3 units up to October. In the midstream, mesohaline salinity was observed during January to March period, and it later changed to limnohaline in May. This situation continued up to October, and then the salinity increased in November and became mesohaline in December. In the upstream locations, salinity was oligohaline during the December and May period, while it was limnohaline (< 0.2) during the rest of the period (Figure 2a, b and c). During the study period overall, the surface water temperature ranged from 27.3 to 33.4°C. However, the water column was warmer during the January - May period in KBW.

Spatially the temperature varies 3°C between down and upstream but the seasonal changes were low (Figure 3a).

Water column turbidity was found high in the downstream (1.6- 21.6 NTU in surface and 5.0 – 24.3 NTU in the subsurface) followed by mid-stream (1.3 - 9.14 NTU in surface and 3.0 – 14.3 NTU in the subsurface) and upstream (1.2 - 6.6 NTU in surface and 1.8 -8.1 NTU in the subsurface). The water column turbidity was found to be the lowest everywhere in the study area during the December-February period. Then the turbidity increased 2-3 folds high by May and June and continued to be high till October (Figure 4).

3.1.2. Dissolved oxygen and nutrients

Dissolved oxygen in the water column was high during the entire study period, being higher in the upstream throughout the study period (4.1 - 7.7 mg.L⁻¹ in downstream; 6.0-9.5 mg.L⁻¹ in midstream and 7.0-9.5 mg.L⁻¹ in upstream locations, Figure 3b). Nitrate was found high throughout the study period with the highest during the SWM (21µM) followed by post-SWM (13µM) and pre-southwest monsoon (12µM) (Figure 5a). Silicate was found very high in the upstream location and phosphate in the downstream region. Silicate concentration was noticeably high (124 µM) during the SWM, while higher (4.3 µM) phosphate was observed during the PRM (Figure 5b and c).

3.2. Phytoplankton biomass (Chl-*a*)

The total phytoplankton biomass distribution in the study locations are presented in Figure 6a. Total phytoplankton was always high in all the locations, and it ranged from 2.21 - 10.77 mg.m⁻³ in the downstream region, 2.58 - 5.93 mg.m⁻³ in mid-stream and 1.71-7.97 mg.m⁻³ in the upstream locations. In the entire study area, the biomass was low during December-February (< 4 mg.m⁻³), as compared to the other periods. During the onset of the SWM, it increased two to three folds compared to the PRM in the entire study area. The contributions of various size groups to the total biomass is presented in supplementary material 2. Nanoplankton contributed most significantly to the total biomass (54.6-86.7% in the downstream; 46.1-83.1% in midstream; 57.2-85.1% in upstream), followed by microplankton (ranged from 9-37.1% in downstream; 6.1-68.5 % in midstream; 9.4-25.8% in the upstream). Microplankton contribution to the total biomass was more significant during May - October period. Spatially, pico-plankton contribution to the total biomass was found high in the upstream locations compared to the downstream and mid-stream regions.

3.3. Bivalve larval abundance

Black clam undergoes several morphologically different life stages (Figure 6b) before settling down to the bottom; these include eggs, and larval stages such as trochophore, veliger and pediveliger (Figure 7). In the present study, black clam larvae were found during the entire sampling period, though their

abundance varied spatially and seasonally (Figure 8c). Over the seasons, the total abundance of the larvae ranged from 7.57 - 118.1 No.m⁻³ in the downstream, 10.04 -493.84 No.m⁻³ in the midstream and 18.39 - 139.57 No.m⁻³ in the upstream. Spatially, black clam larval abundance was high in the midstream followed by upstream (station 3) and least in the downstream. Black clam larval abundance was low in the entire study area during the SWM (June-September). In the downstream, bivalve larval abundance (Figure 8c) was the lowest during the SWM, increasing gradually during the retrieval phase of the monsoon (October and November). this was found to be associated with the salinity increase from limnohaline/ oligohaline to oligohaline/mesohaline conditions in the study area. In the mid-stream locations, larval abundance was the highest during the Jan-March period, associated with the mesohaline salinity conditions that prevailed there. It was the minimum during the Southwest Monsoon (June-September). Later during the post-monsoon, the larval abundance gradually increased, again associated with the increase in salinity from limnohaline to oligohaline levels. In the upstream, the black clam larval abundance was the highest during February and March and low during the SWM.

The contribution of various life stages of the black clam to their total larval abundance is presented in Figure 9. Eggs contributed more to total abundance, followed by veliger and pediveliger stages (Figure 9). The size distribution of different life stages of black clam in all three locations was quantified. Irrespective of the time of collection, the egg was larger sized in the midstream (av. dia. 60-75 µm) compared to the downstream (av. dia. 60-65 µm) and upstream regions (av. dia. 60-70 µm). A similar spatial trend was found in the larval stages as well. Veliger larval size in the midstream (av. 90-105 µm) was higher than the downstream (av. 80-95 µm) and upstream (av. 80-100 µm). The pediveliger also was large-sized in the midstream (av. 140-165 µm) than the downstream (av. 135-150 µm) and upstream (av. 135-160 µm).

3.4. Ecological relationships

The relation of the hydrographical parameters and bivalve larval distribution is clear in RDA Triplot. In Triplot, monthly observations are displayed by blue circles, and environmental and biological variables are denoted by solid red and dotted blue arrows, respectively (Figure 10). The direction of a parameter arrow indicates their increasing gradient, and the angle between two parameter arrows represents how closely they are correlated. The temporal shift in the hydrographical parameters and their influence in bivalve larval distribution was well- reflected in the RDA Triplot (Figure 10). The results of RDA showed that the selected environmental variables together could explain around 49.82 % of the bivalve larval distribution. The Monte Carlo test indicated that the ordination of all RDA axes was significant (P<0.05). The increasing gradients of turbidity and nutrients and decreasing gradients of salinity along with the observations of June, July and August indicate that the riverine flux dominates during that period, as evident in salinity overlaid contour plots. The bivalve larval abundance axis was

oriented along the right side of the plot, and the salinity overlaid plots clearly showed that bivalve larval abundance was high in mesohaline (salinity 5-18) conditions, compared to other situations. The low abundance of black clam larvae found during the SWM period was positively linked to the low salinity and high turbidity in the study region.

4. Discussion

The water column in the study area was warmer during the January-March period compared to the rest of the sampling period due to weak wind and high solar insolation during the period (Figure 3a). A clear spatial difference in salinity was observed from the downstream to upstream regions during the December-March period, which is a typical characteristic of the study region during the non-monsoon period (Figure 2). During the December-May period, the river influx into the study area was low, and as a result, salinity incursion through tidal activity attained dominance at that time. Salinity was in the mesohaline levels during December in the downstream region, which increased to euhaline/polyhaline during the January-March period. Recent studies (Arunpandi et al., 2020a,c; Haridevan et al., 2015; Sooria et al., 2015) shows a similar seasonal salinity distribution as in this study wherein limnohaline to mesohaline levels occur in the midstream during the transition from the SWM to the Post-southwest monsoon (PSWM), and mesohaline levels during the January-March period. In the upstream region of the KBW, salinity was limnohaline during the SWM. It increased gradually to oligohaline level during the January-March period (Figure 2a, b and c), which is a typical seasonal characteristic of the study region (Anjusha et al., 2018a; Haridevan et al., 2015; Sooria et al., 2015).

Turbidity is a good indicator of the estuarine status concerning the flooding and re-suspension of bottom sediments. In this study, turbidity was always higher in the downstream region (Figure 4). During January-March, turbidity was higher downstream as compared to midstream and upstream, which was associated with tidal re-suspension of bottom sediments - a phenomenon observed to be quite usual during the period (Menon et al., 2000; Sooria et al., 2015). During May and June, turbidity increased two to three folds higher than the PRM period, throughout the study area, which was associated with floodwaters and land runoff related to the SWM rainfall (Nasir, 2010) (Figure 4). High nitrate levels occur in KBW, and its distribution here was quite unusual as compared to other estuaries of India, because of several non-point nutrient sources in the study area associated with agricultural fields, and domestic and municipal effluents. (Jagadeesan and Jyothibabu, 2016; Madhu et al., 2007; Shoji et al., 2008; Sooria et al., 2015; Thottathil et al., 2008). Silicate was found to be higher in the upstream region while phosphate was higher downstream; this spatial pattern of silicate was evident in earlier studies as well (Anjusha et al., 2018a; Sooriya et al., 2015).

Phytoplankton biomass was high and always $>3 \text{ mg.m}^{-3}$ in the study area. The biomass increased several folds during the SWM, given the substantial river inputs (Figure 6). It has been recently found

along the southwest coast of India that low solar radiation associated with cloudy sky and high nutrients enhances biomass of large-sized phytoplankton in the surface layers during the southwest monsoon (Anjusha et al., 2018b; Jyothibabu et al., 2020). A situation similar to the above was observed to prevail in the present study area during the onset and early SWM, showing enhanced phytoplankton (unusually long-chain forms) production. On a spatial scale, picoplankton abundance was found to be high in the upstream region, associated with high abundance/blooms of freshwater cyanobacteria (Arunpandi et al., unpublished data).

An earlier study in the KBW showed that black clam abundance depends on food availability and suitable hydrographical conditions (Arun, 2009). Past benthic studies focusing on bivalve distribution in the KBW confirmed that black clams contribute more than 90% of the total bivalve abundance (Arun, 2009; Gopal et al., 2014; Pandiyarajan et al., unpublished data). An experimental study showed that the meroplanktonic stages of black clam size varies from egg (55 μm), earlier veliger (95 μm) to later 'D' shaped veliger (140 μm). This observation corroborates the present measurements of black clam larval stages from egg (60-75 μm) to veliger (80-105 μm) and pediveliger (135-165 μm) (Achary, (1988). Black clam attains sexual maturity at a length of 11 to 15mm (Achary, 1988). Reproductive stages of black clam include the undifferentiated stage (adult), early gametogenesis, late gametogenesis, mature, partially spent and spent. The studies of Achary, (1988) and Arun, (2009) showed that the ratio of the developing and matured organisms varies periodically. Also, laboratory experiments and field studies in the past showed that the rapid change in salinity and pH induce changes in the breeding/spawning of clams (Achary, 1988; Arun, 2005; Arun, 2009). It was noticed earlier that in clam beds, the bivalve spawning is influenced by the changes in salinity (Deshmukh, 1972; Ranade, 1973). Some other studies have shown that black clam in the KBW breeds twice a year, with peak production in November-December and a second one during PRM (April-May). In contrast, this study showed that the black clam in the KBW is a continuous breeder as the larval presence was evident throughout the sampling period in all three selected sampling locations. Also, while it was also observed in the present study that peak larval production occurred twice a year, the peak times did not coincide precisely at the same time in the upstream, midstream and downstream locations.

The observed difference in time of the peak spawning in the study locations in the KBW could be attributed to the temporal variation in the prevalence of optimum hydrographical conditions in these locations on a temporal scale, as they were located well apart. It also conveys the view that the same sedentary living resource may show noticeable spatial differences in their reproductive responses in the same ecosystem (Anjusha et al., 2018a), in connection with the time lag in the setting of the most conducive hydrographical environments on a spatial scale (Arunpandi et al., 2020a,c; Haridevan et al., 2015).

Black clam larval samples in the present study were analysed with a combination of microscopes and FlowCam (Supplementary material 3). However, the morphological identification of the black clam larvae was confirmed on a molecular basis in another distinct study carried out along with this study, utilising larval subsamples collected in this study (Parvathi et al., unpublished data). It was noticed in this study that the black clam larval abundance was less in the entire KBW during the June-September period. Their abundance increased subsequently in October and November in the downstream and midstream; this is the time when the salinity in these regions changed from limnohaline to oligohaline levels (Figure 8c). In December, due to the low freshwater influx from the rivers, oligohaline conditions prevailed in the midstream, which favoured black clam spawning and a subsequent increase in the larval abundance there. However, in the upstream location, this transition occurred during January, which may be the reason for observing the first larvae peak in December and January in that region. In essence, the present study underscores the view that the time of the peak spawning of the black clam varies spatially and seasonally in the study area (Figure 8c). This variation is linked to the transition of salinity levels (limnohaline to oligohaline) in the different regions; this salinity transition downstream occurs in October, in the midstream in November and December and the upstream in December and January.

It was reported earlier that the construction of TB decreased the black clam resources in the Vembanad section of the KBW (Arun, 2005). It was also noticed that black clams could not reproduce well in extremely low salinity, with the size of the organism remaining small under such environmental conditions (Suja and Mohamed, 2010). In the present study, it was quite evident that limnohaline to oligohaline transition had an apparent inducing effect; mesohaline salinity was found to be optimum for the production of bivalve larvae. The intrusion of saline water during PSWM season induces the initial spawning of matured organisms in the entire stretch of the estuary. In this context, it is essential to determine how the closure of the TB during the non-monsoon period influences the black clam stock in the region. The closing of the TB after the monsoon would prevent the entry of saline waters into its southern part, whereas it increases the salinity in the northern side of the TB. This causes failure in the natural formation of the extended oligohaline/limnohaline region towards the south of the barrage, most ideal for the black clam spawning. All these, in turn, affects the natural spawning pattern and larval production on both sides of the TB. Another negative impact of the TB on live black clam beds is associated with the occasional sudden opening and closing of its shutters. The opening of the TB shutters causes salinity shock to the black clam living on both sides of the barrage, and it leads harmful to black clam as they are sensitive to sudden changes in the salinity of an environment (Achary, 1988). These observations from the KBW could be relevant and applicable to many similar water bodies in other parts of the world having hydraulic barriers to regulate the natural flow of water. In respect of the demand of the growing world population for a cheap protein and mineral (calcium) source, especially in Asian countries, the black clam remains a cheap natural source that contributed about 5.4 million tonnes in 2015

(Wijsman et al., 2019). On the other hand, environmental modifications like regulation of natural water flow through barrages could adversely affect the clam production potential and slowly decline and removal from the system (Ens et al., 2004; Steeves et al., 2018). Therefore, we propose here the necessity to have a proper scientific management mechanism in place to regulate the periodic opening and closure of the TB, as well as ensure the sustainable utilisation of the black clam resources in the KBW.

5. Conclusion

This study, based on monthly analysis of black clam larval abundance and associated hydrography in three locations in the upstream, midstream and downstream of the KBW discuss some critical observations. First, this study presented the view that the black clam stock in the KBW is a continuous breeder, as their larvae were found throughout the monthly sampling in locations; this is against the traditional belief that this resource breeds only twice a year. Further, it was observed that mesohaline was the optimum salinity condition for spawning and larval production. Two annual peak larval production times were found in all three locations, which was closely associated with the prevalence of optimum salinity conditions. On a yearly scale, based on the time difference in the prevalence of mesohaline conditions in the three locations studied, the timing of the peak larval production also showed a spatial difference. The salinity shift from limnohaline to oligohaline/mesohaline appeared to have an inducing effect on the spawning, and larval production in all three locations studied. The closure and opening of the TB cause salinity shock to black clam and noticeable changes in the occurrence of the oligohaline and mesohaline conditions in a large area on both its sides, causing changes in the spawning pattern and larval production of the black clam.

Declaration of Competing Interest

The author's state that they have no known competing financial interests or own relationships that could have seemed to influence the work stated in this paper.

Acknowledgements

The authors thank the Director, CSIR- National Institute of Oceanography (CSIR-NIO), India, for facilities and support. We thankfully acknowledge all of our colleagues in the National Institute of Oceanography, India who helped in carrying out the fieldwork. The first author acknowledges the Department of Science and Technology (DST) for providing him DST-INSPIRE Fellowship (IF120804). This is NIO contribution XXXX.

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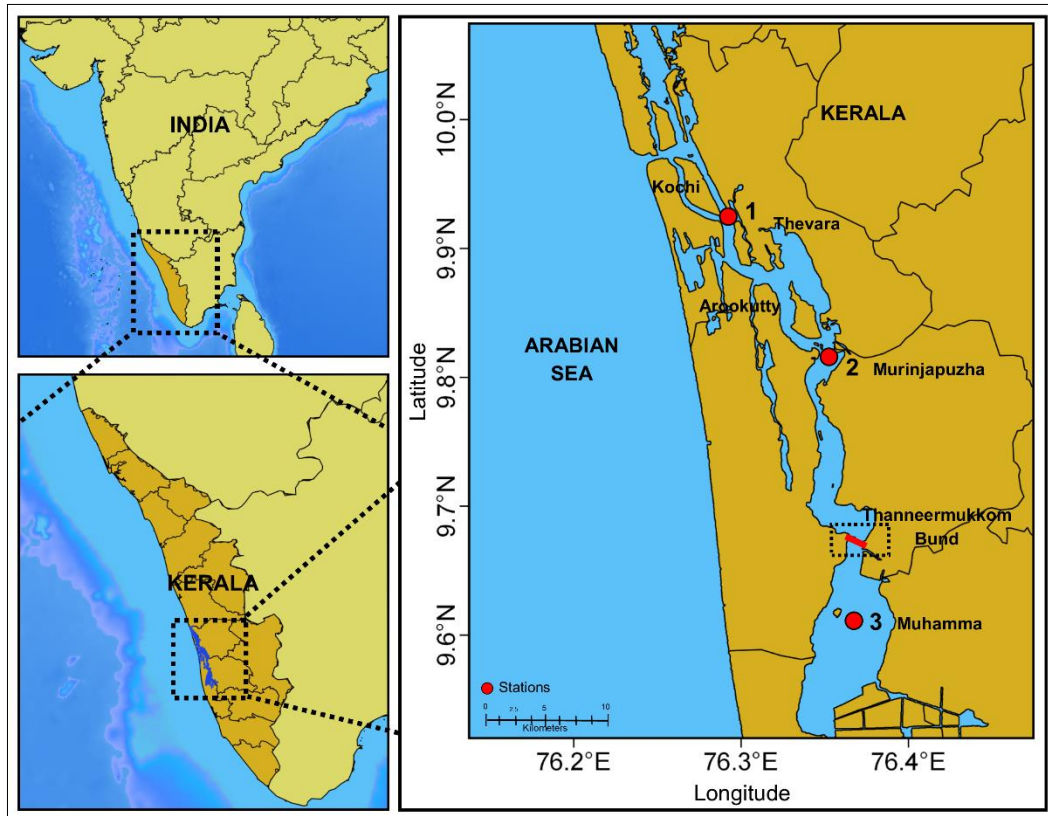


Figure 1 Sampling locations in the Kochi backwaters, along the southwest coast of India.

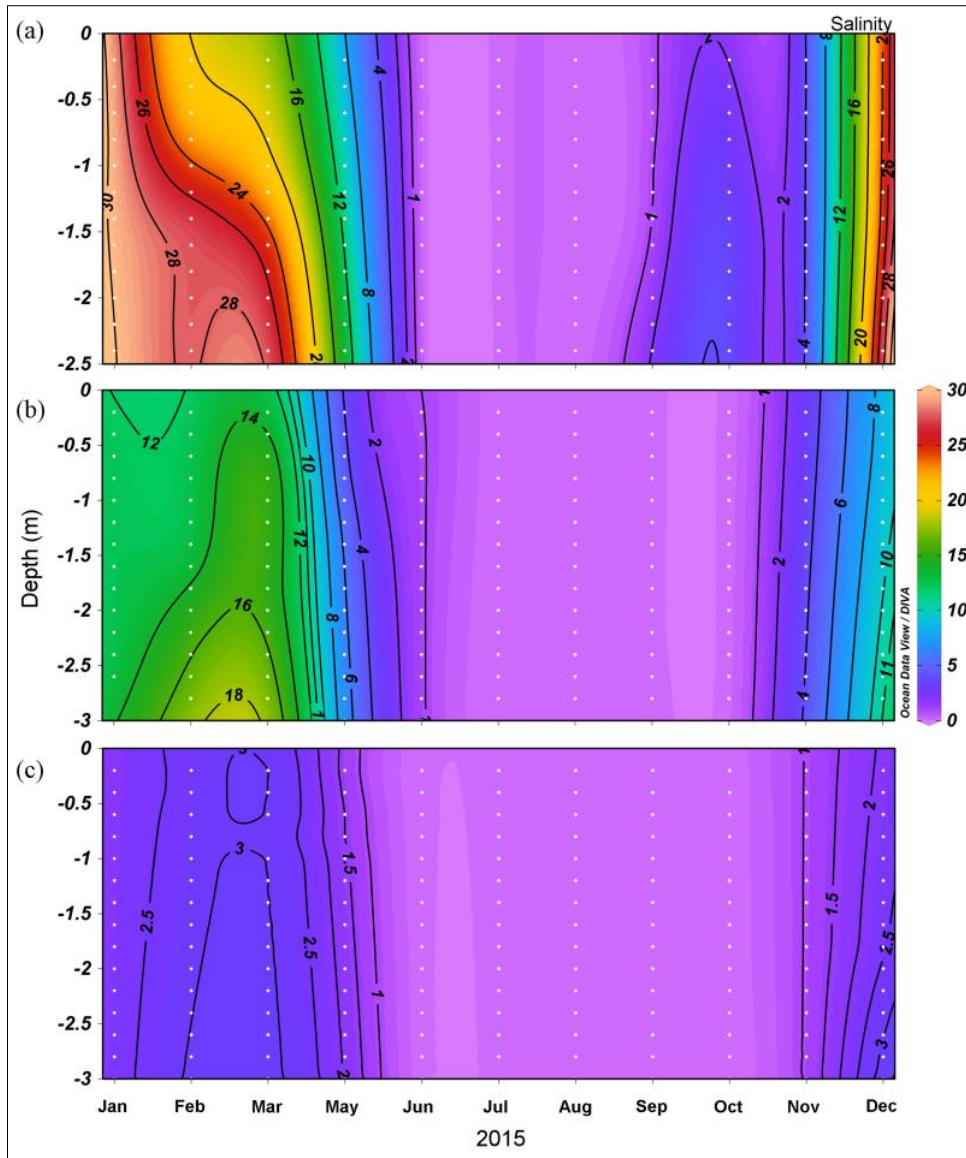


Figure 2 The vertical distribution of salinity at (a) station 1 (Thevara), (b) station 2 (Murinjapuzha) and (c) station 3 (Muhamma) during the study period between January to December.

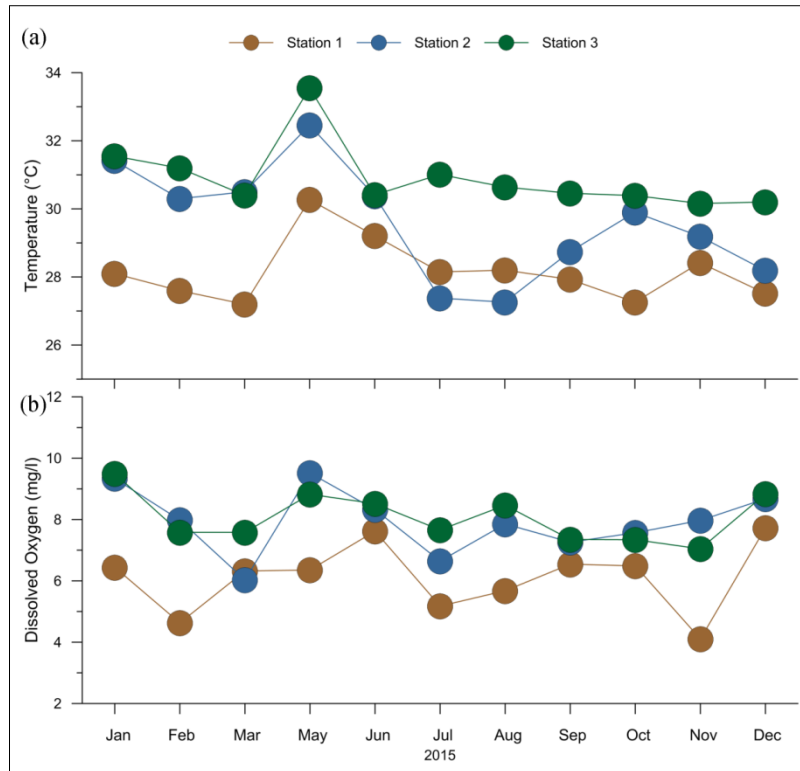


Figure 3 Temporal variations in (a) temperature and (b) dissolved oxygen during the study period from January to December 2015 (except April). The coloured lines indicate stations, brown (Station 1), blue (Station 2) and green (Station 3).

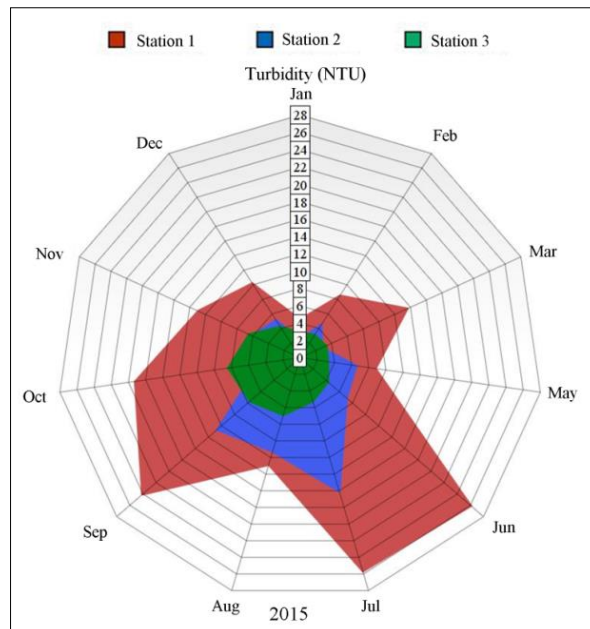


Figure 4 Temporal changes in surface turbidity (NTU) in the study area (a) station 1(Thevara), (b) station 2 (Murinjapuzha) and (c) station 3 (Muhamma) during the study period between January to December 2015.

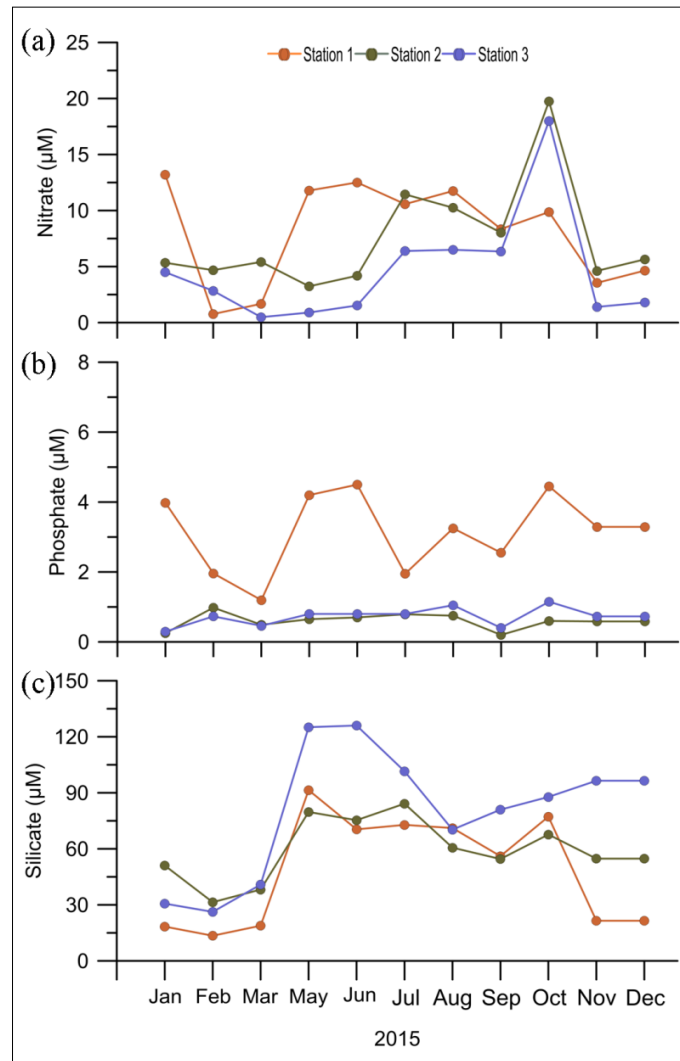


Figure 5 Temporal variations in nutrients (a) nitrate, (b) phosphate and (c) silicate during the study period. The coloured lines indicates station, brown (Station 1), green (Station 2) and blue (Station3).

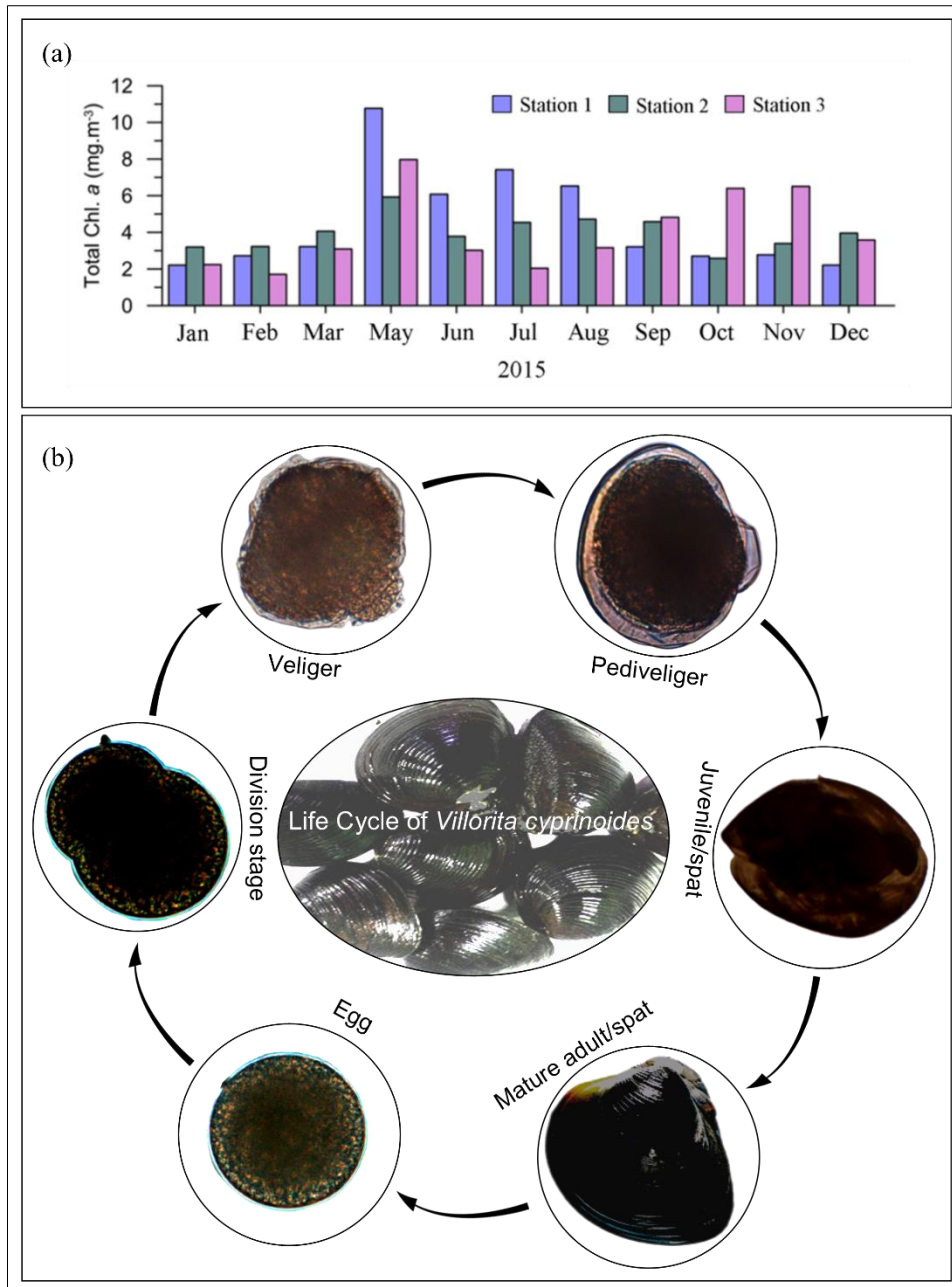


Figure 6 Shows (a) the temporal distribution of total chlorophyll *a* in the surface water in the study area and (b) the life cycle stages of *Villorita cyprinoides*.

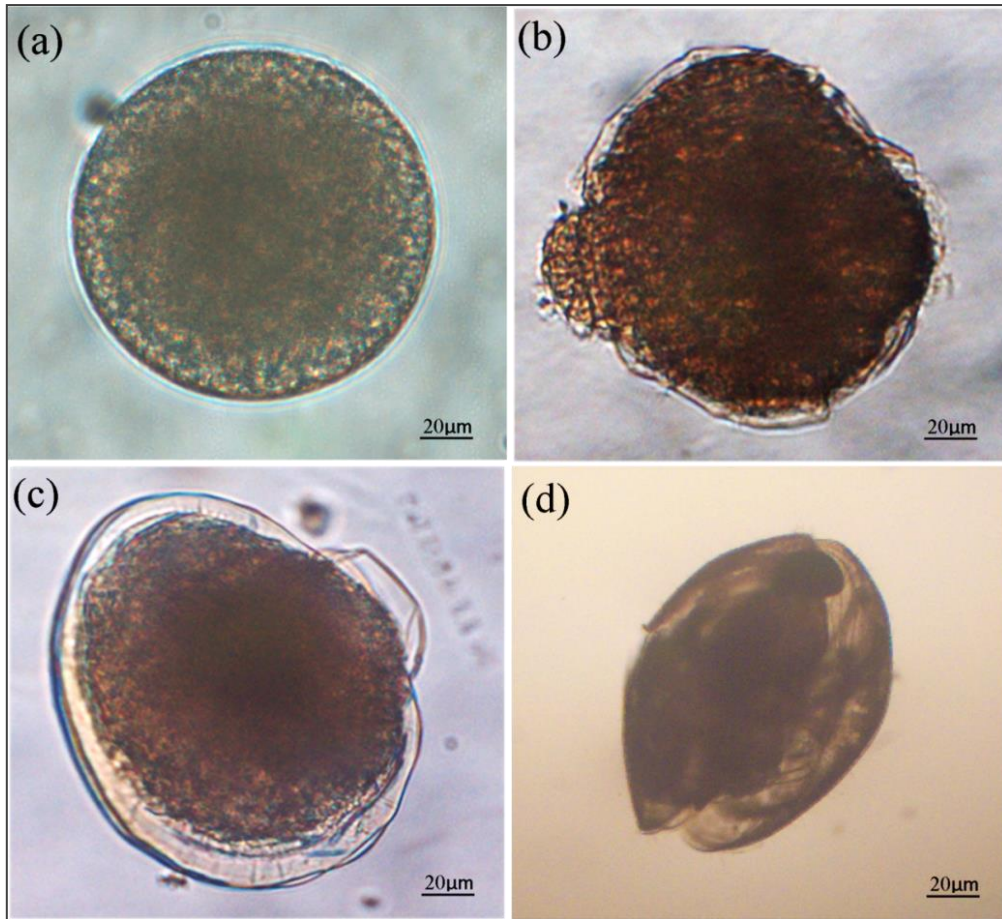


Figure 7 Panels (a - d) show observational evidences for the meroplanktonic life stages of *Villorita* larvae under an inverted microscope. (a) egg (b) veliger/trochophore (c) pediveliger and (d) spat/mature larvae.

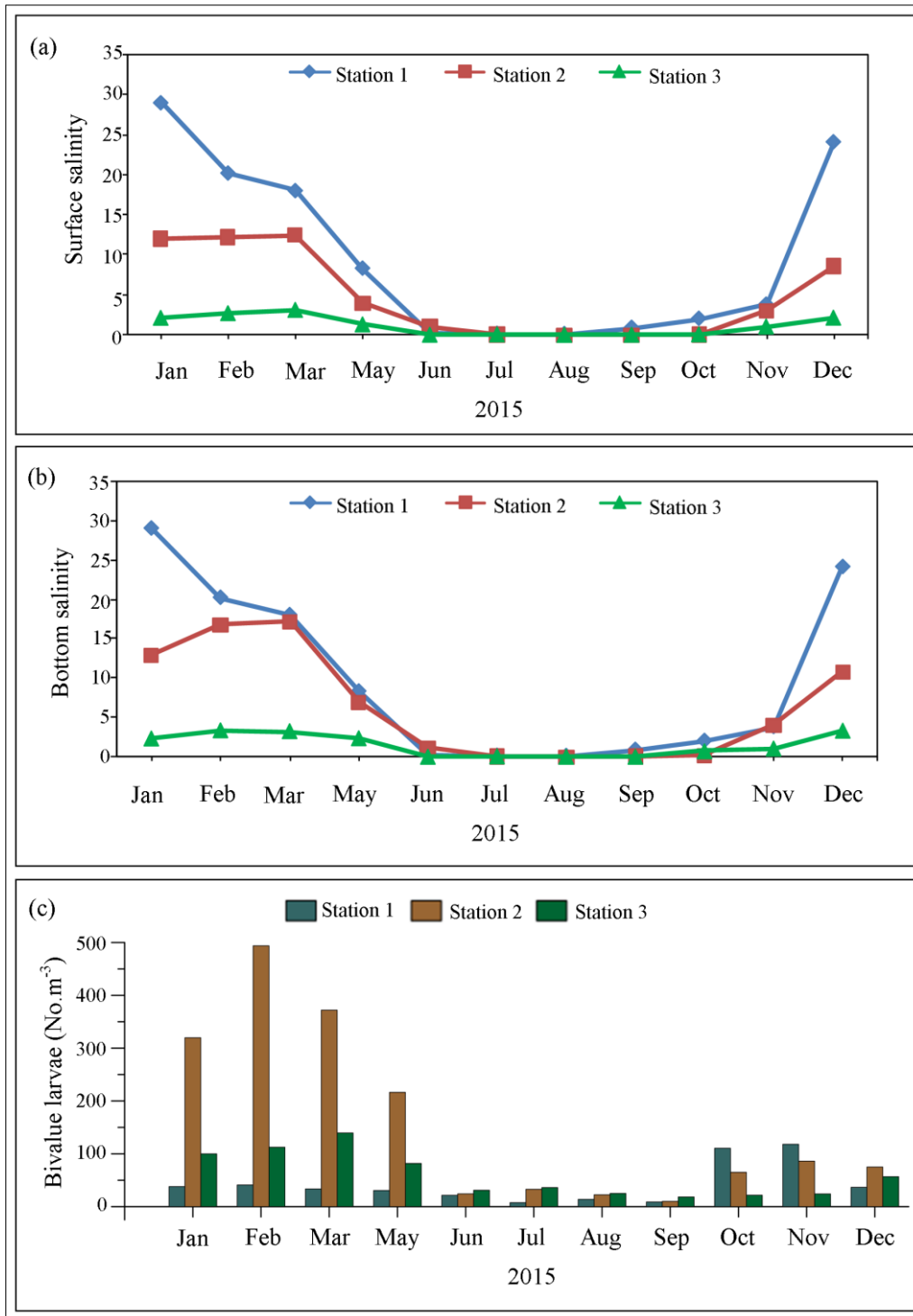


Figure 8 Indicates the temporal changes in the surface (a) and bottom (b) salinity and (c) shows the distribution of black clam larvae at three locations in the study area from January to December 2015 (except April).

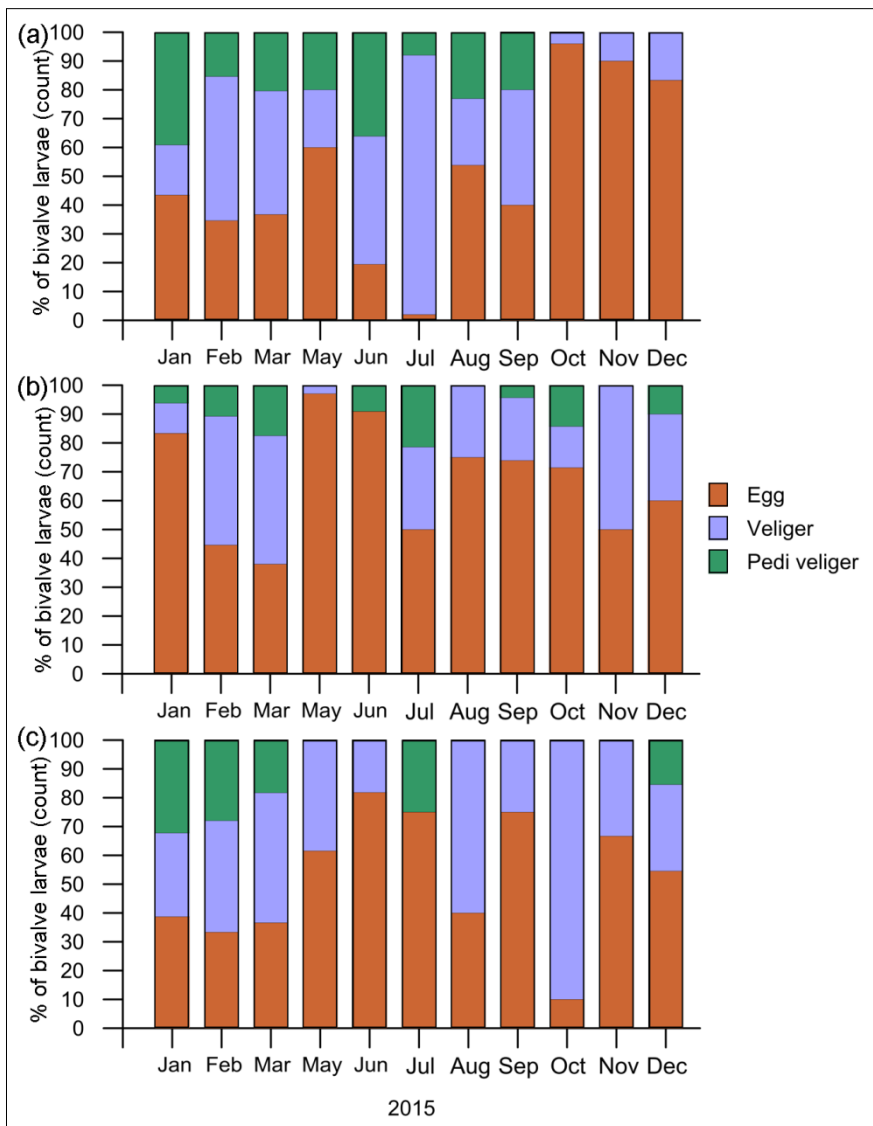


Figure 9 The percentage of different larval stages during the study period in three locations (a) Station 1, (b) Station 2 and (c) Station 3

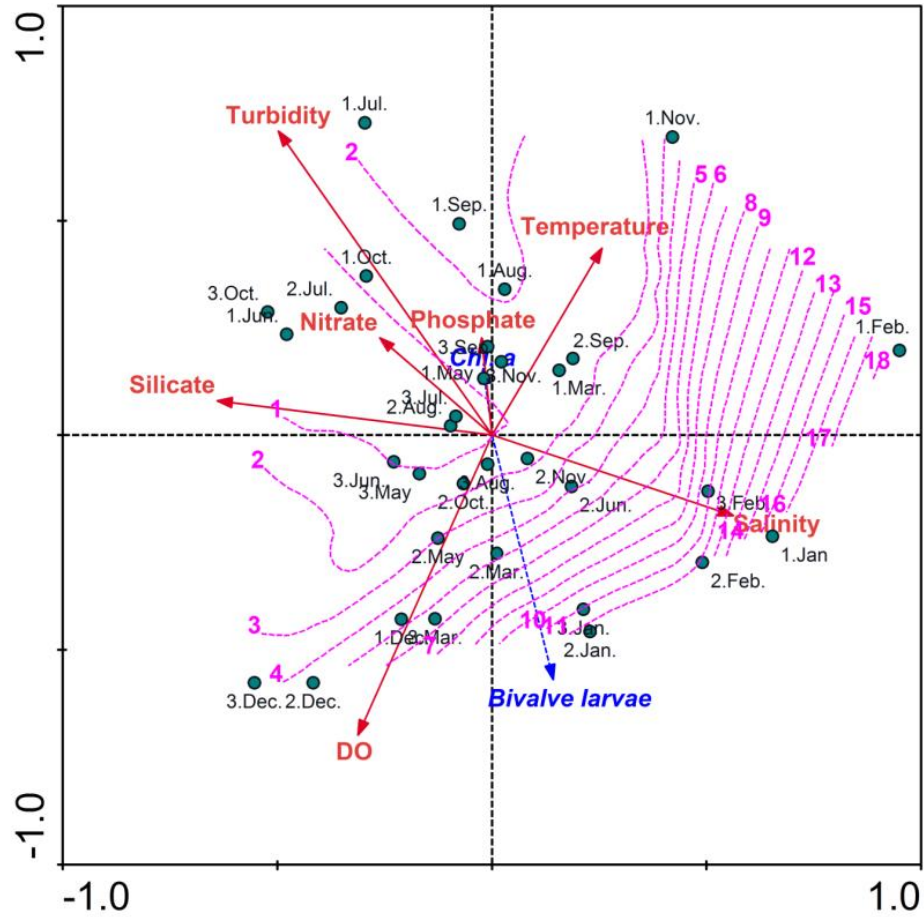
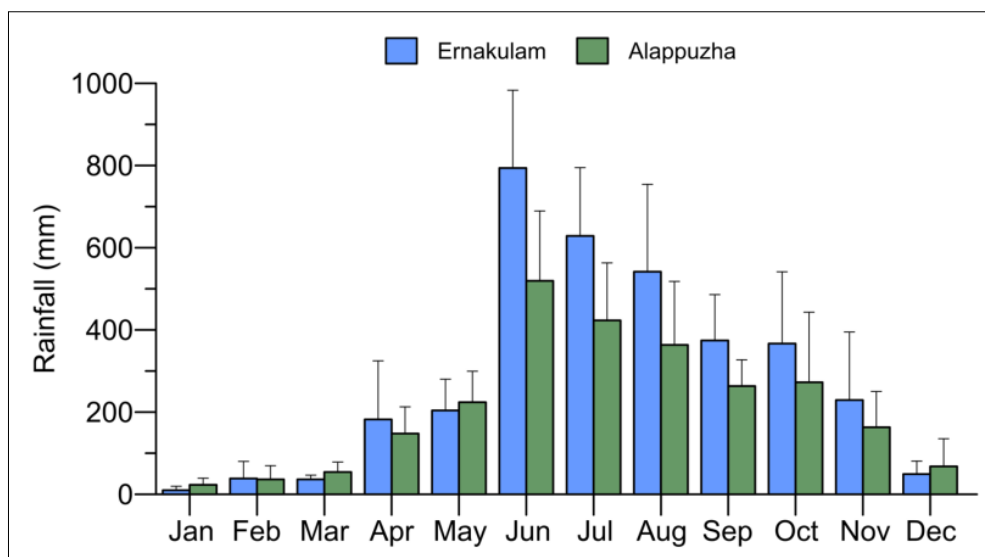


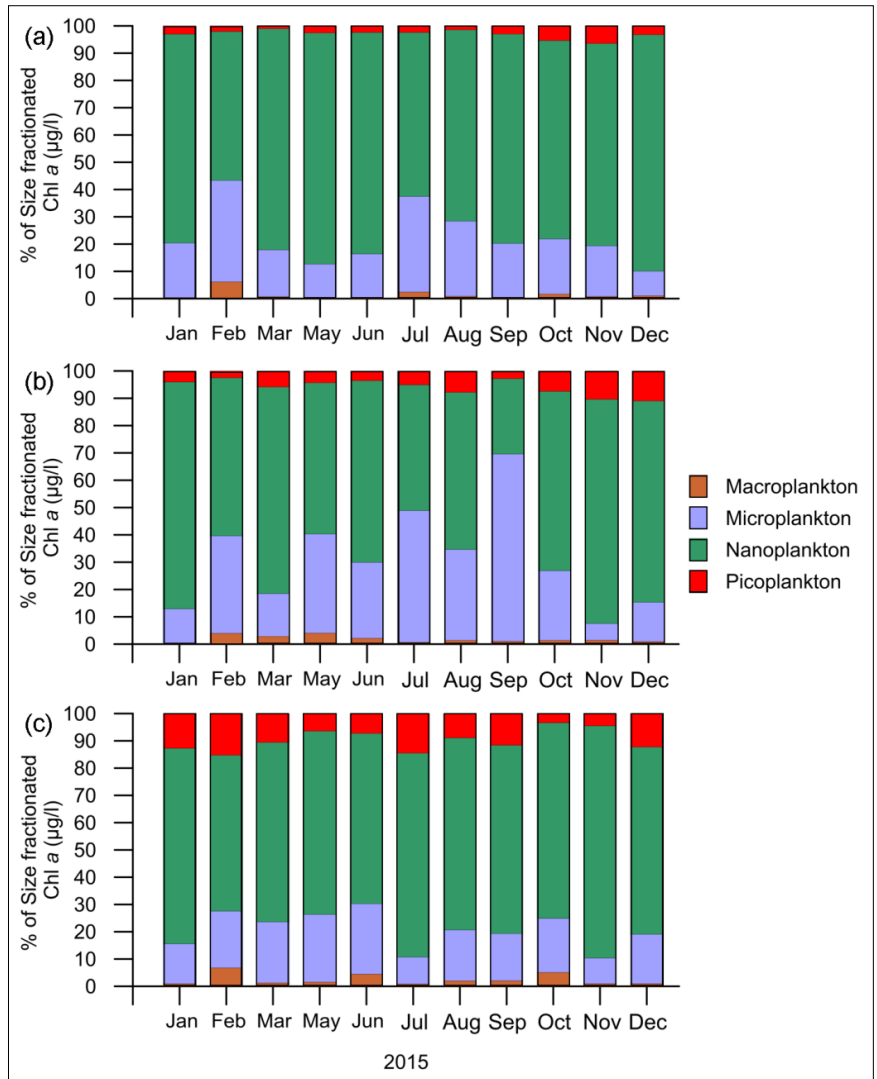
Figure 10 RDA Triplot showing the overall ecological inter-relationship of black clam larvae with other environmental variables. High abundance of larvae was found in moderate salinity, temperature, nutrients and turbidity indicating the post Southwest Monsoon period. RDA Triplots, which display sampling months, and biological (dotted blue) and environmental variables (red lines) were displayed by arrows; salinity was denoted with dotted pink colour.

Table 1 ANOVA results of salinity and bivalve larval abundance comparisons within and between stations. * $p < 0.05$; ** $P < 0.01$; ns- non significant.

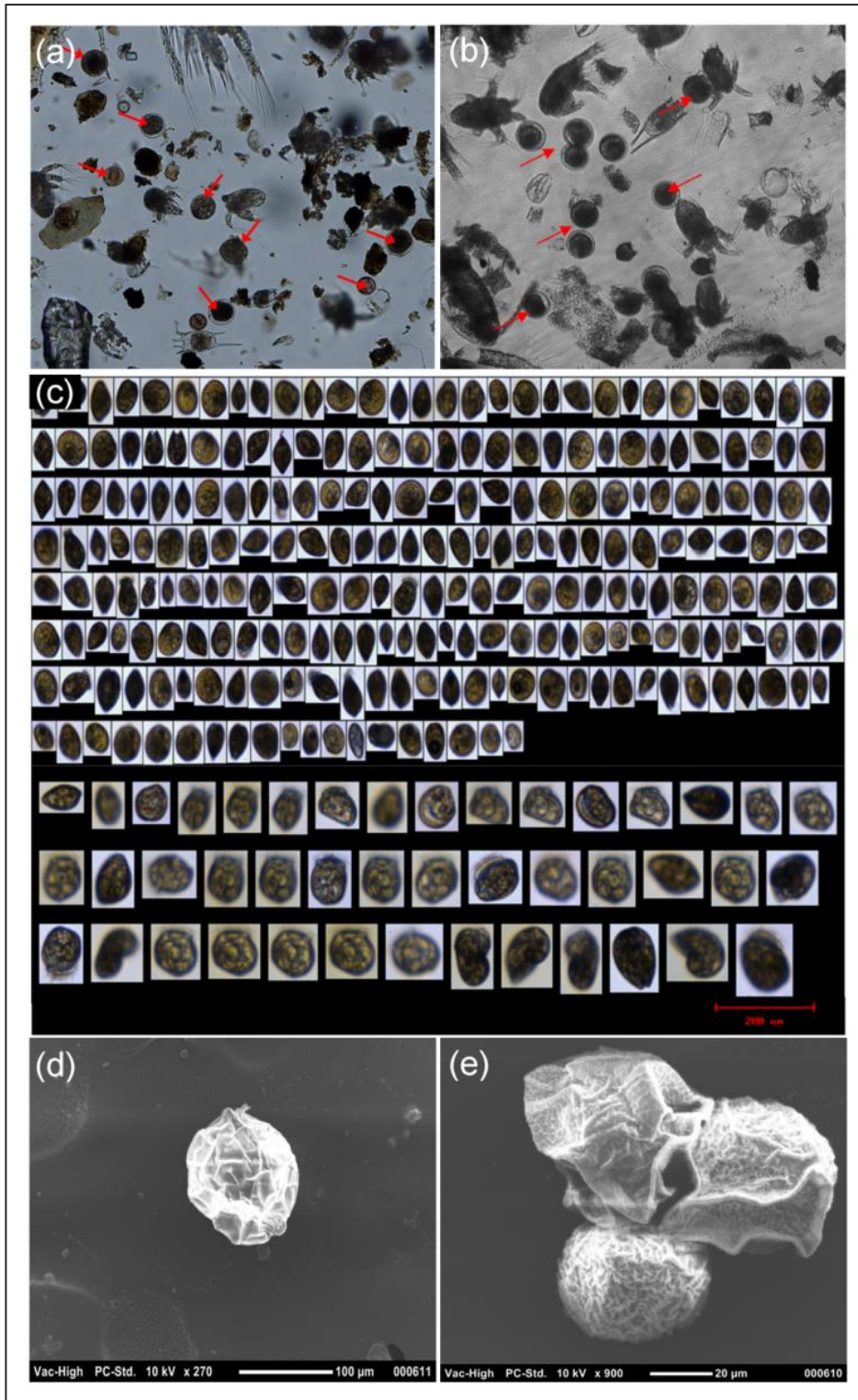
ANOVA		F value		p value		
Salinity	Seasonal differences with in station					
	Station 1	5.30		p=0.034*		
	Station 2	8.93		p=0.009**		
	Station 3	10.41		p=0.005**		
	Seasonal differences between station					
	Station 1	9.26		P=0.006**		
	Station 2	0.88		P=0.449 (ns)		
	Station 3	6.49		P=0.03*		
	Bivalve larval abundance	Seasonal differences with in station				
		Station 1	9.28		p=0.008**	
Station 2		23.9		P=0.0004**		
Station 3		22.69		p=0.0005**		
Seasonal differences between station						
Station 1		23.03		P=0.0002**		
Station 2		3.38		P=0.08 (ns)		
Station 3		7.76		P=0.02*		



Supplementary material 1 Monthly rainfall (five year mean) in Ernakulam and Alappuzha districts. Source: IMD, India.



Supplementary material 2 Contribution of different phytoplankton size fractions to the total chlorophyll *a* in the study area. (a), (b) and (c) indicate station 1, 2 and 3.



Supplementary material 3 Photomicrographs of black clam larvae. Panels (a and b) show the microscopy images of the samples from the study area, (c) shows FlowCAM images and (d) and (e) Scanning Electron Microscope (SEM) images.