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Research Article

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Ecology and Distribution of Copepods from the Salt Pan Ecosystems of Mumbai, West Coast of India

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Abstract

Ecology, distribution and diversity of Copepod collected from two salt pans of Mumbai, India, are presented. Copepods, the main zooplankton components, consisted mainly of *Bestiolina similis, Acartia southwelli, Oithona* sp., *O. similis, O. hebes* and *Mesochra sp.* The species distribution showed pulses and peaks with harpacticoids dominating in extreme environmental conditions. The diversity and seasonal variations of species were considered in relation to environmental conditions. The study contemplates on the modification of a diverse community of copepods of the creek salt works into a simplified ecosystem of low complexity based on the influence of environmental factors on the copepods density. The prevailing environmental conditions of the salt pan systems are unique and play a prominent role explaining about 80% of the seasonal variations in the secondary production ($P<0.05$). Both have emerged as independent systems maintaining their identity. Cyclopoids and harpacticoids were observed in swarms tiding over adverse conditions by dormant eggs. This study on density and diversity of copepods, for the first time in India, lacking from saltpans of India, shows dormant eggs constitute a biodiversity bank, offsetting environmental disasters and helping in repopulation and conservation.

Keywords

Copepods; Community structure; Salt pan; Ecosystem; Mumbai

Introduction

Solar salterns represent an extreme environment, with high concentrations of sodium chloride, occasional rapid changes in water activity, low oxygen concentrations and high UV radiation. They are characteristically exposed to a wide range of environmental stress, mainly due to salinity changes. The distinct feature of the brine ecosystem is its biotic simplicity, and the number of species in each trophic level is low, which can be attributed to stress situations on the biotic population.

Scientific investigations of the salt pans along the coast of India are confined mostly to the population and biological studies of *Artemia* and mysids [1] because mysids crustaceans are one of the major components of coastal and estuarine zooplankton communities and for many organisms that use these areas as nurseries, mysids play an important role as a resource. Mysids are an important link in the food web of a coastal ecosystem [2] and are prey for various fish [3-5] as well as for invertebrates, birds and seals [6] thereby linking primary and secondary production to a higher trophic level.

Zooplankton in general has been investigated by [7], particularly in copepods. Rattan and Ansari had earlier studied *Fabrea salina* from Bhayander salt pans [8]. There are also two new species namely *Pseudodiaptomus pankajus* and *Acartia sarojus* (Copepoda: Calanoida), described by Madhupratap and Haridas [9,10] from the Gulf of Kutcch. Though copepods form a significant part of the zooplankton, there are no qualitative studies of the group from salt pans of India. The qualitative and quantitative changes in community structure can be analysed by population parameters such as diversity or by multivariate methods that reveal the relationship of biological communities with their environment [11]. The present study contemplates how a diverse community of copepods of the creek gets modified within the salt works into a simplified ecosystem of low complexity and aims to reveal the influence of environmental factors on the density of copepods.

Study Area

The two saltpans studied are located at Thane (19° 03´ 36” N lat. and 72° 57´ 33”E long.) and Bhayander (19 ° 17´ 42” N, lat. and 72° 48´ 42” E long.) in Mumbai, (18° 55´ N Lat. 72° 50´ E long.), the largest metropolitan city on the west coast of India. The Arabian Sea traverses the entire coastline of the city on the western side, and along the eastern side, it is separated from the main land of Konkan by Thane creek Mumbai harbour. The two saltpans are connected to the Arabian Sea through the Thane and Bassein creeks. The interior part of this complex creek system is fringed by rich mangrove vegetation and the land around is used for cultivation and as salt-works. The tides in this area are of mixed type and are predominantly semidiurnal. The mean height of the spring tide is 3.7 m. The layout of a typical salt pan is given in Figure 1. The salt pan system studied is divided into reservoirs, condensers and crystallizers. During every spring tide, water is taken continuously for 2 to 4 days into the reservoir for storage as per the requirement of salt production. From the

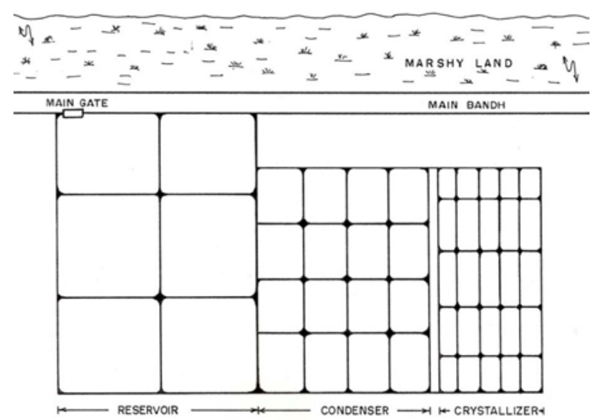

Figure 1: Lay out of saltpan (modified by Biju and Panampunnayil, 2010) [1].

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reservoir, the water is transferred to the condenser for evaporation and after a few days transferred to the crystallizer through a channel. This special ecosystem is characteristically subjected to a wide range of environmental stress manifested mainly through salinity changes.

Materials and Methods

In the present study, two salt pan systems adjacent to the creek environment of Bhayander and Thane were selected. A total of 10 stations including the creeks spread over to Bhayander (B1-B5) and Thane (T1-T5) (Figure 2) systems were considered. At each system, 1 indicates creek location, 2 and 3, the reservoirs, and 4 and 5, the condenser and crystallizer, respectively. More details of stations are given in Table 1.

Zooplankton samples were collected every month for a period of 15 months from May 1991 to July 1992, using plankton net having a mouth area of 0.08 m^2 and mesh size of 0.1 mm fitted with a calibrated TSK flow meter. Further details regarding collection and analysis are given by Mustafa et al. [7].

In the statistical methods, as an a priori step to statistical analysis, the variables were transformed, determining the optimal transformation, using 2 way Tuckey's test of additivity [12]. Comparison among sampling stations, seasons and between species, based on species abundance, was carried out according to the strategy outlined by Field et al. [13]. A 3 way ANOVA was applied for Bhayander and Thane creeks taken together to compare within and between creeks, between species, between months and the first order interactions between these factors with respect to appropriately transformed copepod species abundance and water quality parameters. For analysing data on community structure, initially the biotic relationship between any two samples was distilled into a coefficient measuring similarity (or dissimilarity) in species composition. Secondly, stations were classified into groups [14] or by mapping the station interrelationships in an ordination by nonmetric multidimensional scaling (nMDS) [15-17]. In order to link the multivariate community structure to environmental variables, two different but complementary statistical techniques, (1) the nonparametric method, BIO-ENV procedure [16] and (2) the parametric method called the multiple regressions by step up method was also applied [18,19]. For this study niche breadth is calculated over the study period for each species in the 5 stations of Bhayander and Thane saltpan ecosystems and a comparison is made so as to classify them as healthy and nonhealthy regions. Niche breadth [20] was calculated as

$$nb_i = EXP\{-\Sigma\left[\left(n_{ij}/N_i\right) x\log_e\left(n_{ij}/N_i\right)\right]\}$$

Where n_{ij} = number of individuals of the ith species in the jth station of each location. N_i is the total abundance of the ith species over all the stations. Q-mode and R-mode factor analysis [21] for row and column normalised data after varimax rotation to simple structure [22], were also adopted for a complete description of the ecosystems.

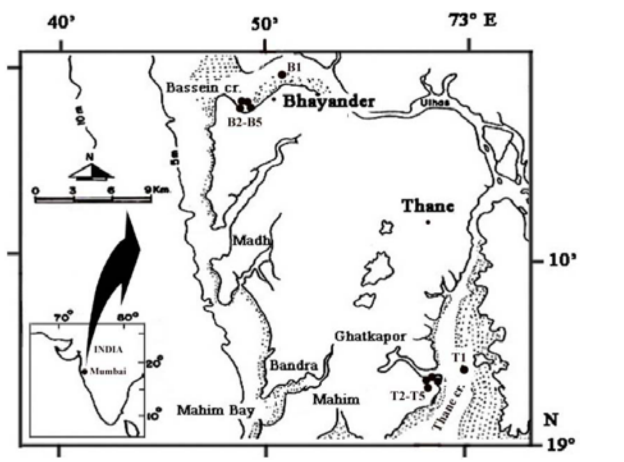

Figure 2: Locations of stations in saltpans of Mumbai, India.

Table 1: Details of stations at Bhayander and Thane saltpans.

Locations	Stations	Position		
		Latitude (°N)	Longitude (°E)	Depth (m)
Bhayander Creek	B1	19° 18' 48"	72° 51' 02"	1.00 – 2.00
Bhayander Reservoir 1	B2	19° 17' 45"	72° 48' 49"	0.90 – 1.30
Bhayander Reservoir 2	B3	19° 17' 42"	72° 48' 42"	0.90 –1.30
Bhayander Condenser	B4	19° 17' 45"	72° 48' 42"	0.30 – 0.40
Bhayander Crystalliser	B5	19° 17' 42"	72° 48' 45"	0.08 – 0.12
Thane Creek	T1	19° 03' 42"	72° 58' 19"	1.00 – 2.00
Thane Reservoir 1	T2	19° 03' 37"	72° 57' 19"	0.90 – 1.30
Thane Reservoir 2	T3	19° 03' 36"	72° 57' 33"	0.90 –1.30
Thane Condenser	T4	19° 03' 47"	72° 57' 16"	0.30 – 0.40
Thane Crystalliser	T5	19° 03' 42"	72° 57' 19"	0.08 – 0.12

Results

Water quality parameters and nutrients

In the statistical methods, an a priori step to statistical analysis was applied to get the variables transformed, determining the optimal transformation, using 2 way Tuckey's test of additivity [12]. In this test the log transformation,

$Y=(X+1)^{0.0015,}$ that is $Y=\log_{10}(X+1)$,

$P<0.05$ and $p=0.0015$ was obtained as the optimal transformation for the parameters.

At the Bhayander system, temperature varied from 23.2°C (B2, Dec. 1991) to 44.5°C (B5, May 1991) (av. 28.4°C). In general, there were prominent differences in water temperature between B1 and B5, with a maximum difference during May 1992 (7.5°C). The variation in water temperature at the Thane system was from 20.0°C (T2, Jan. 1992) to 43.0°C (T5, May 1992) (av. 30.1°C). The water temperature differences between T1 and T5 were prominent, and the maximum was recorded in May 1992 (9.5°C). Area wise, station wise and season wise differences in temperature values were all significant ($P<0.01$) (Table 2). The nMDS analysis grouped the stations in Bhayander and Thane area (Figure 3A) with the reservoir in Bhayander giving different temperature reading from condenser and crystalliser, but the creek reading was different from all these three, whereas in the Thane creeks, only the creek area was different from the other three. The annual difference in temperature (°C) increased from creek to the crystallizer in the following rate,

15.5 (B1) → 16 (B2/B3) → 18 (B4) → 19.5 (B5)

12 (T1) → 18 (T2/T3) → 20.5 (T4) → 21 (T5)

Fluctuations in pH values at the Bhayander system were

Table 2: 3 way ANOVA for comparing between areas, between stations and between seasons.

Source	Temperature	pH	Salinity	Suspended solids	Dissolved oxygen	Phosphate	Nitrite	Nitrate	Ammonia	dof	α
	F ratio	F ratio	F ratio	F ratio	F ratio	F ratio	F ratio	F ratio	F ratio		
Between areas	17.64	NS	11.69	6.89	7.82	NS	12.42	NS	14.45	1,56	0.01
Between stations	19.21	12.26	64.04	43.72	9.42	11.26	2.38	10.26	4.95	4,56	0.01
Between seasons	63.56	6.55	21.19	27.85	6.58	1.99	2.47	2.52	3.56	14,56	0.01

α: level of significance; dof: degrees of freedom; F: Snedecors F statistic; NS: Not Significant

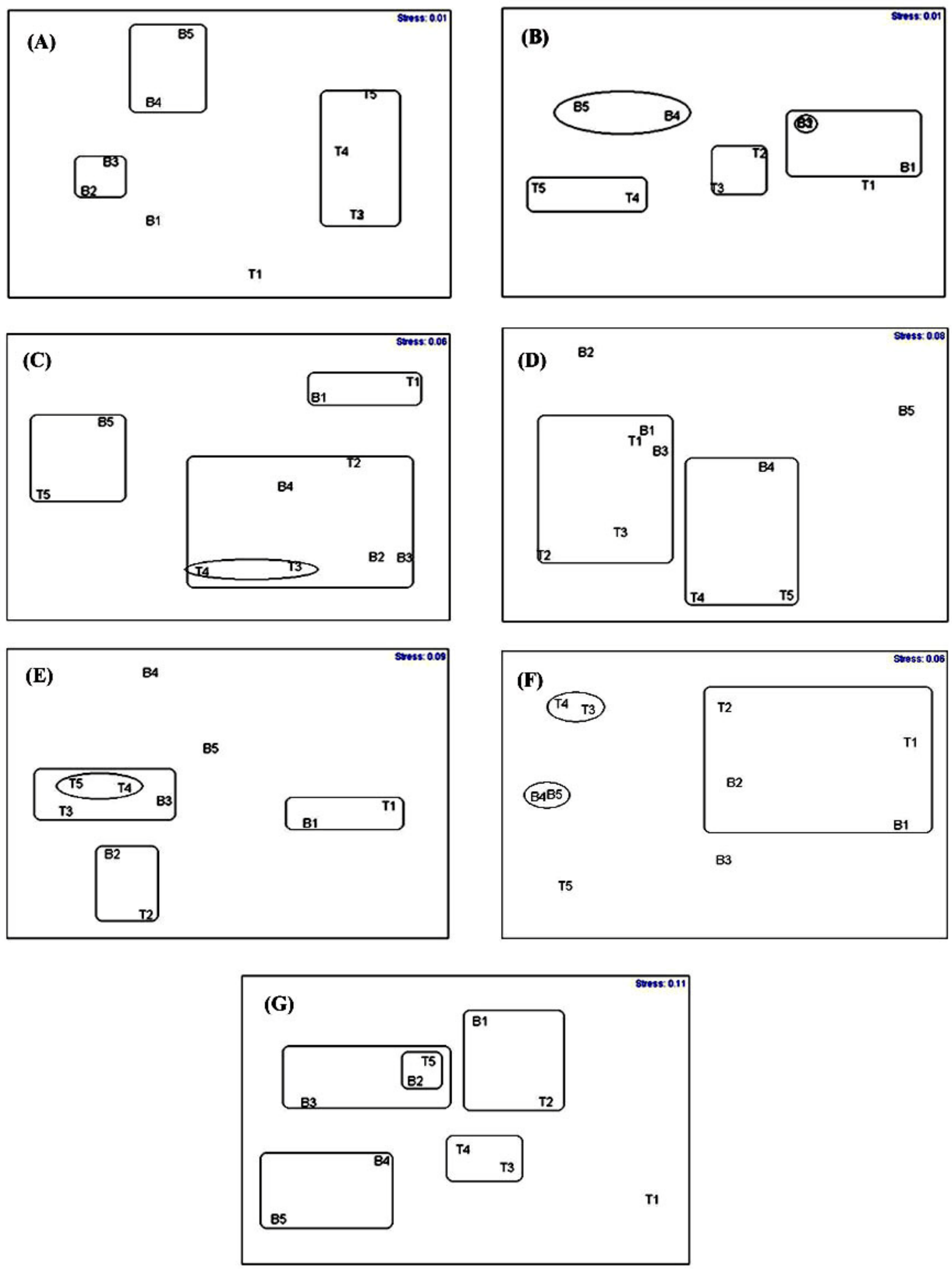

Figure 3: nMDS analysis for stations based on monthly data on (A) Temperature, (B) Salinity, (C) Suspended solids, (D) Dissolved oxygen, (E) PO4-P, (F) NO3-N and (G) NH4-N.

observed to be in the range of 6.9 to 8.6. At the Thane system, the pH variations were relatively higher (7.0 to 9.4) compared to those at the Bhayander system. Bhayander and Thane creeks showed no significant differences as the difference in pH values existing between stations as well as between seasons remained the same in both the creeks (P>0.05) (Table 2).

Salinity variations were enormous at different locations of the Bhayander system. At B1, the condition was typical of a creek environment with maximum salinity in the pre-monsoon month of March 1992 (36.1) and minimum during the monsoon period in July 1992 (0.9) with an annual average value of 24.9. During the monsoon period, (July-August) salinity reached almost fresh water conditions. The post-monsoon period indicated fluctuation in salinity and later, steadily increased to attain the maximum level in pre-monsoon period. In the reservoir (B2 and B3) and crystallizer (B5) there were drastic increases in salinity depending on the season. At B2 and B3 salinity fluctuations were at the respective rates of 7.2–71.5 (av. 38.2) and 7.2–71.8 (av. 38.8). Throughout the study period, salinity was high at B4 except during peak monsoon seasons, fluctuating from 8.8 (August 1991) to 178.5 (June 1992). Maximum salinity was 360.7 (B5, June 1992) and minimum was 8.5 (B5, August 1991) with an average of 133.0.

Similar trends were observed in the Thane system with maximum values during pre-monsoon period. At creek T1, it varied between 11.2 and 38.2 (av.29.3) comparable to an estuarine zone. The low salinity condition during monsoon changed to relatively higher salinity during post-monsoon and pre-monsoon periods. Salinity range at T2 and T3 were 7.5 to 99.9 (av.50.2) and 3.3 to 183.4 (av.65.1), respectively. Throughout the study period, salinity range at st. T4 was high, except during the monsoon period. The observed mean value for pre-monsoon, monsoon and post-monsoon were 166.6, 42.3 and 96.2, respectively. At T5 maximum salinity reached a level of 344.6 in January 1992 while the minimum of 3.3 was observed in July 1991 (av.165.9). The mean value for pre-monsoon was much higher than for monsoon and post monsoon. Difference in salinity observed between creeks, between stations and between months were all significant (P<0.01) (Table 2). Difference obtained was clear from the mode of clustering of the stations by nMDS, in which condenser and crystalliser in Bhayander and Thane were separated. Reservoir in Thane area was separated from the other two. In the Bhayander, reservoir and creek did not differ much, based on salinity (Figure 3B).

At the Bhayander system, suspended solids varied at a wide range of 52 (B5, Feb. 1992) to 6220 mg/l (B5, May 1991) with an average of 964 mg/l while in the Thane system, it was in a range of 48 (T5, July 1992) to 7101 mg/l (T5, May 1991) with an average of 1084 mg/l. At T1 the fluctuation was from 77–1075 mg/l (av.337 mg/l). The two creek areas showed significant differences in suspended solid values. This difference was reflected in the different stations as well as between months (P<0.01) (Table 2). nMDS analysis showed that the crystallisers in both areas were separated from creeks based on suspended solids concentration. Reservoirs and condensers showed similarity in suspended solid values within and between Bhayander and Thane (Figure 3C). Suspended load showed wide fluctuations at both the systems with maximum load during pre-monsoon period.

Along the Bhayander system, dissolved oxygen levels varied from 0.6–9.5 mg/l. Dissolved oxygen levels at B5 were often low and the observed range was 0.6–6.5 (av. 3.5 mg/l). The variation in dissolved oxygen at the Thane system was from 1.4–12.0 mg/l. The difference in the dissolved oxygen values between areas, between stations and between months were highly significant (P<0.01) (Table 2). Significant seasonal difference occurred in the two creeks ($F_{(14,149)}$ >3.54). nMDS analysis showed that the prefixed station grouping in Bhayander and Thane as creeks, reservoirs, condensers and crystallisers did not hold good, particularly for DO in Bhayander (Figure 3D). Peak in DO was observed either during monsoon or post monsoon period. Within the salt pan system there were wide fluctuation in DO and the level sometimes went down the normal concentration probably associated with relatively higher water temperature. Various salts dissolved in water lowered its ability to hold oxygen and hence high saline water will have low DO.

A wide fluctuation in phosphate concentration (μg/l) was observed at the Bhayander system (0.1–30.1) compared to the Thane system (0.1–12.4). In both systems, variations in nitrate concentration were at a wide range of 0.1-54.5 (μg/l) at Bhayander and 0.3-66.3 (μg/l) at Thane. Fluctuation in nitrite concentration at the Bhayander system was observed at a range of 0-23.0 (μg/l) while that at the Thane system, it was between 0 and 17.4 (μg/l). In the Bhayander system, the ammonia concentration showed a variation of 0.1-20.1 (μg/l). Variation in ammonia at the Thane system was from 0.1-31.4 (μg/l) (Av. 3.9 (μg/l)). With respect to PO_4-P (Figure 3E) and NO_3-N (Figure 3F) the significant difference in their values in the different stations (P<0.01), and in the different months (P<0.05), occurred more or less in the same pattern in the two creeks (P>0.05). However, with respect to NH_4- N (Figure 3G), difference in their values in the two creeks differed significantly with respect to stations (P<0.01) as well as with respect to seasons (P<0.01) (Table 2). From nMDS analysis, similar to DO distribution, based on NH_4-N distribution also, the demarcation of the stations in the Thane creek did not hold good. Nutrients indicated wide fluctuations and the trend is comparable at both the systems. Concentration of nutrients especially nitrate was very high at the creek stations due to influx of waste water.

The water quality indicated glaring differences between the creek and salt pans. The decreasing trend observed for the nutrients was by a factor of 5.2 for phosphate, 6.8 for nitrate, 2.6 for nitrite and 12.5 for ammonia. However, the difference between the two systems was not well defined.

Bhayander system

Community structure of copepod: Twenty-one species of copepod belonging to 10 genera were recorded at the Bhayander system, which included 16 Calanoida, 4 cyclopoids and one harpacticoids species. Copepod species present in each station (B1-B5) are given in Figure 4. At B1, a total of 20 species were observed with *Acartia southwelli*, *Acartia tropica* and *Oithona brevicornis* being the abundant species. From B2, a total of 19 species were recorded where Mesochra sp., *Acartia spinicauda, Acartia southwelli, Paracalanus crassirostris* were the common species. At B3, out of sixteen species, *Acartia southwelli, Oithona sp.1, Acartia tropica* and *Acartiella sewelli* were common. The species at B4 decreased to 12. *Acartia southwelli*, *Bestiolina similis* , *Mesochara sp* and *Oithona sp1* were abundant in this station and *Oithona sp 1* was the most common species. At B5 also twelve species were observed in which *Mesochra* sp. *Oithona sp.*, *Oithona similis*, *Acartia tropica* and *Pseudodiaptomus annadalei* were encountered. *Mesochra* sp. and *Oithona sp.* dominated the area contributing more than 75% of the total copepod population.

Distribution and diversity: The percentage of copepod in the total zooplankton at B1 ranged from 6.3 in December to 99.0 in February 1992, registering an average of 68.1%. The copepod population in B1 varied from 17–10280 inds./m^3 (av.1760 inds./m^3). The lowest density was recorded in May 1992, when copepods contributed only 12.8% of total population. The highest population was recorded in February 1992, when its contribution was 99.0%. Species richness index was lowest during July (1.13) and highest during May (4.02). Average richness index was 2.45 with 48.59% variation over all the months. Heip's evenness index for the copepod species, which measures the extent of uniformity in the distribution, was 0.94 with 63.26% variation, with the minimum value (0.09) during February and the maximum value (1.71) during December and January. This is attributed to the species such as *Bestiolina similis* and *Oithona brevicornis* which are dominant, implying less uniformity in the distribution of copepod species at B1. Moreover, the Shannon Weaver index of diversity was only 1.03 with 53.44% seasonal variations, implying that only a moderately stable environment prevailed in this area during the study period with the minimum value (0.24) during February and the maximum (2.00) during November. Pielou's measure which gives the dominance index for each month showed that the species dominance varied between 0.25 (June) and 1.13 (October), with a mean dominance of 0.58 and distributional variation of 53.45%. Simpson index of concentration showed an average value of 0.42 with 51.03% spatial variation. Since the seasonal variations for all the characteristics of the species were not negligible, it indicates that this area is species specific, as indicated by the high dominance of the species *Bestiolina similis*, *Oithona brevicornis* and *Acartia southwelli* during different periods (Figure 4). Niche breadth of the species ranged between 1.07 (harpacticoids sp.) and 4.68 (*Acartia spinicauda*). R-mode factor analysis has grouped the 15 months of collection into 4 significant factor groups ($\lambda>1$) of which the first 3 are differential factor groups imparting with 23.92, 18.58 and 8.39% of the temporal variability (Table 3 and Figure 4A). These 4 clusters are identified as the periods with high relative abundance of *Bestiolina similis*, *P. adjuna*, *Oithona hebes,* and *Acartia tropica* respectively. There are 4 distinct clusters of species at 60% similarity level containing (1) *Mesochara* sp., *P. tollengirae*, *P. aurivilli* and *A. tortaniforsis, (2) Centropages dorsispinatus and P. annandalli*, (3) *Pseudodiaptomus ardjuna* and *Acartia spinicauda* and (4) *Bestiola similis* and *Para. crassirostris* associated at 40 % similarity level (Figure 4A). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated nitrate and ammonia to be the limiting factors whereas temperature and suspended solids to be controlling factors for copepod abundance at creek area (Table 4). BIOENV analysis showed a high correlation of 0.789 between the species *Bestiolina similis, Pseudodiaptomus ardjuna, A. tropica, Harpacticoids sp. and nitrate.*

At B2, copepod contribution varied between 33.3% (June 1991) and 100% (July, January 1992), with an average value of 85.8%. The density of copepods varied between 43 and 280571 inds./m^3 (av.37664 inds./m^3). The lowest and highest copepod populations coincided with those of the total zooplankton population. Margalef richness index varied from 0.75 (November) to 2.79 (March) with an average richness factor, 1.67 and 51.45% seasonal variability [23]. Shannon and Weaver diversity index varied between 0.33 (May) and 3.19 (July), with an average index value of 0.89 and a variation of 66.14% [24]. Heip's average evenness index for the distribution of individuals over the species was 0.89 with 73.95% variation over the months [25]. Pielou's species dominance was 0.90 with 66.14% variation [26]. Species concentration factor determined by Simpson index has an average value of 0.35 with 66.13% variation [27]. As for niche breadth, it was small with low variation, ranging between 1.02 (*Oithona* sp.) and 3.10 (*Mesochra* sp.). R mode analysis has grouped the 15 months of study into 5 significant factor groups, of which the first 4 form the differential factors which provide with 16.84, 17.98, 15.07 and 13.98% of the temporal variability. These unique periods are identified by the abundant occurrence of the *O. hebes, Oithona*

Table 3: R-mode factor analysis for grouping of months In the Bhayander and Thane salt pan area. (B5 and T5 were not taken due to few number of species.

Station		Temperature	Salinity	DO	Phosphate	Nitrate	Ammonia	Species dominating
B1	Factor group 1	27.8 – 34.0	28.6–35	4.4–5.2	3.4–8.9	0.2–54.5	0.7–9.0	*Bistiolina similis*
	Factor group 2	23.5 – 28.5	26.6–30.7	3.2–5.8	1.2–3.2	23.8–37.3	0.6–1.3	*Pseudodia. adjuna*
B2	Factor group 1	24.5 – 31.1	7.2–36.3	1.7–6.3	0.1–0.9	3–12.6	0.2–3.0	*Oithona hebes*
	Factor group 2	23.2 – 32.5	15–47.7	4.7–8.7	1.6–2.4	2.4–25.1	0.2–11.0	*Oithona similis*
B3	Factor group 1	26.5 – 39.5	11.4–63.6	4.6–6.8	0.4–2.6	0.8–1.8	0.4–4.3	*Oithona similis*
	Factor group 2	24.2 – 27.8	40.2–62.2	4.6–6.8	0–8.9	11.9–44.2	0.3–1.0	*Acartia southvelli*
B4	Factor group 1	28.0–36.0	44.0–178.5	2.7–3.8	3.7–14.4	0–1.5	0–1.3	*Oithona hebes*
	Factor group 2	26.0–43.0	49.1–108.1	2.2–6.0	0.2–2.9	0.2–7.1	0.2–2.1	*Oithona similis*
T1	Factor group 1	22.0 –34.0	16.3–38.2	3.2–6.2	1.3–12.5	2.1–45.1	0.1–31.4	*Oithona similis*
	Factor group 2	28.0 – 31.0	11.2–36.0	3.4–6.2	4.2–9.8	1.9–19.6	10.4–15.5	*Cyclops sp.*
T2	Factor group 1	31.0–38.0	42.9–99.9	4.0–10.9	0.2–3.1	1.6–16.8	0.1–19.6	*Oithona similis*
	Factor group 2	28.5–36.5	9.9–74.0	5.5–10.3	0.5-0.8	2.0–10.3	0.1–0.6	*Acartia southvelli*
T3	Factor group 1	28.5 –36.5	29.6–89.5	4.4–6.2	1.2–4.0	0.8–9.9	0.3–2.6	*Oithona similis*
	Factor group 2	24.5–37.0	3.3–58.7	5.2–9.6	0.2–2.2	1.9–6.0	0.3–39.3	Cyclops sp.
T4	Factor group 1	21.5 –42.0	189.4–220.6	3.2–5.9	0.9–2.7	0–1.4	0.1–13.0	Mesochra sp.
	Factor group 2	25.0 –29.2	4.0–89.1	1.9–6.3	0.8–1.50	7.9–15.3	3.4–6.1	*Oithona hebes*

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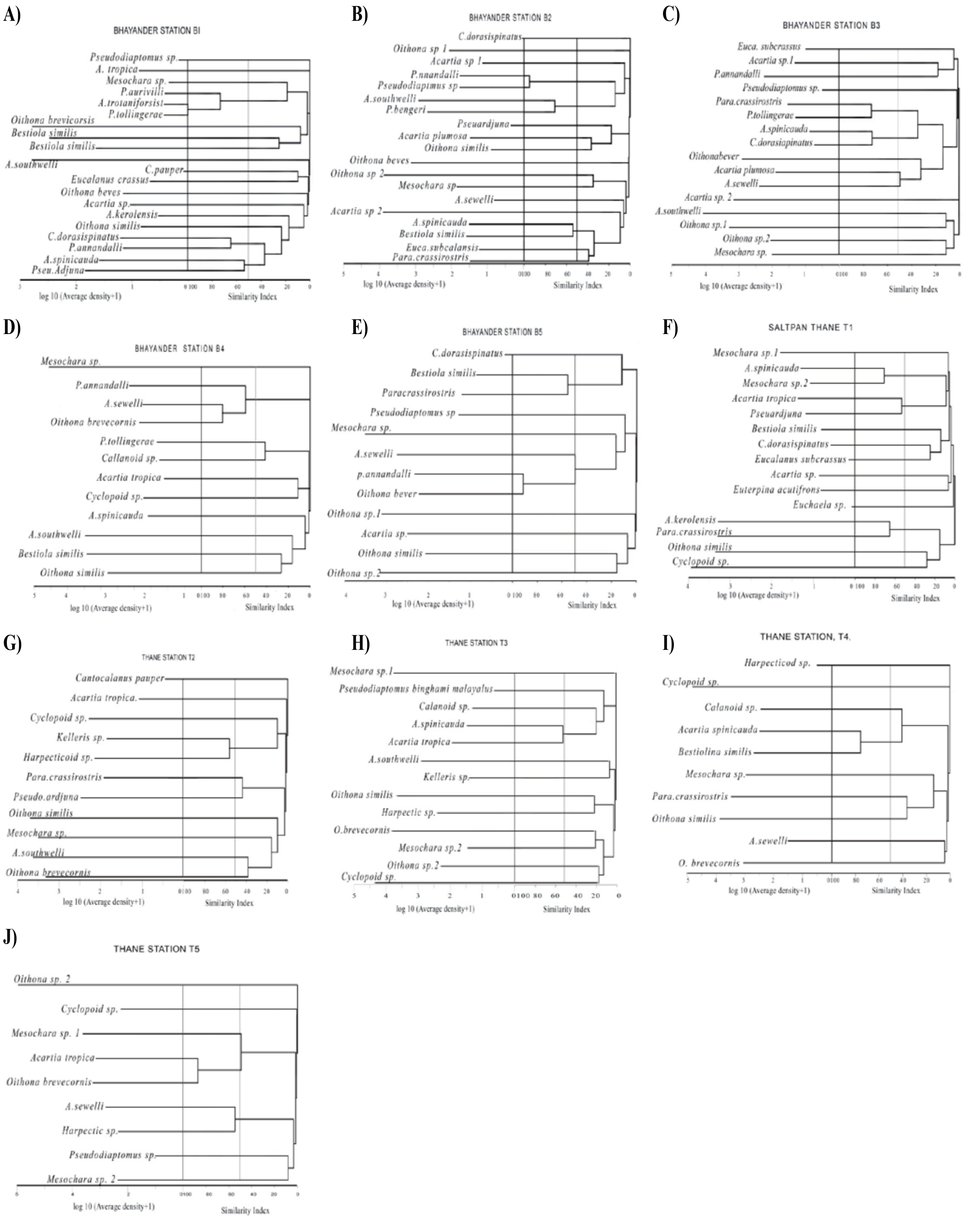

Figure 4: Dendrogram based on cluster analysis for copepod species based on monthly data on species distribution and $\log_{10}$ of average species density over the months at stations (A)B1,(B)B2, (C)B3, (D)B4, (E)B5, (F)T1, (G)T2, (H)T3,(I)T4, and (J)T5 respectively.

similis, and *Mesochra sp.* and *A. Southwelli* (Figure 4B). The indicator species, *Mesochra* sp. dominating this period could tolerate a lower range of temperature, salinity and dissolved oxygen, but a wider range of nutrients. The remarkable occurrence of this species during the period shows the tolerance of this species for lower ranges of heat, high range of salinity, and wide ranges of nutrients. Q-mode factor analysis has delineated 4 distinct clusters from 19 copepod species constituted by (1) *Pseudodiaptomus sp., P. Annadalli* (2) *A. southwelli, P. bengeri* and (3) *A. Spinicauda ,Bestiola similis* at 60% similarity level and (4) *Eucalanus subcrassus* and *Para. Crassirostris* at 40% level of similarity respectively (Table 3 and Figure 4B). The remaining species are not associated, showing their requirement of varied environmental conditions for their survival. Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated nitrate to be the controlling factor whereas salinity and dissolved oxygen to be limiting factors for copepod abundance at reservoir area B2 (Table 4).

Copepods at reservoir, B3 constituted 24.4% in April to 100% in February and June1992 (av. 86.1%). Density ranged from 20 inds./m^3 in April 1992 to 78695 inds./m^3 in November 1992 (av.14994 inds./m^3). The minimum population was recorded in April associated with high temperature and salinity where as the maximum was observed in November 1992 supported by low temperature and salinity. Comparatively few numbers of species were present at B3 with high seasonal fluctuation of 77.03% and average richness value of 1.56. The richness value ranged between 0.57 (May) and 4.82 (December). For all the species distributional characteristics, the variation was almost the same. Species dominance factor was highest in February (1.69) with an average dominance of 0.81. Species concentration factor was very low (average 0.39), varying between 0.03 (May) and 0.71 (November). Species niche breadth was almost the same with the lowest breadth (1.36) for *Centropages dorsispinatus* and the maximum niche breadth (4.78) for *Oithona* sp. R-mode factor analysis for the study period of 15 months has delineated 4 statistically significant factor groups containing 5, 3, 3 and 2 months, which are respectively dominated by *Oithona beves*, *A. Southwelli*, *Acartia* sp. 2 and *P. Annadalei*. The first two factor groups are differential factor groups, as far as the distribution of copepods is concerned at the reservoirs (Table 3). Q-mode factor analysis has delineated 3 clusters from 16 species, which is quantitatively same as that obtained by the Bray Curtis similarity cluster analysis, the clusters having 50 – 70% similarity. These include: (1) *A. sewelli, Acartia plumosa* (2) *Centropages dorsispinatus* and *Acartia spinicauda* in cluster 2 and (3) *Paracalanus crassirostris* and *P. tollingerae* (Figure 4C). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated nitrite and suspended solids to be the limiting factors whereas phosphate and salinity to be controlling factors for copepod abundance at the second reservoir area (Table 4) showing the significant difference between the two reservoirs at Bhayander.

At B4 copepods were absent during June 1991, March and June 1992. Relative abundance of copepods varied from 24.4% (in July 1991) to 100% in May 1991, January, February, May and July 1992. At this station, during the 15 months, only in 8 months more than 1 species were recorded, with species richness varying between 0.68 (October) and 3.33 (January). Comparatively low variation was observed for community structure indices compared to B1, B2 and B3. The indices for richness (1.71), diversity (1.03) and evenness (1.05) are higher than those of the other stations whereas dominance factor (0.73) is lower. Species niche breadth is comparatively lower with maximum value (2.81) for *Oithona similis* and minimum value (1.20) for *Bestiolina similis.* At this station, the study period was classified into 6 significant factor groups of which only the first two factors of months are statistically significant ($\lambda>1$). Factor one is dominated by *Oithona beves,* factor group 2, by *Oithona similis., Bestiolina similis* and *A. southwelli,* the indicator species of factor groups 3 and 4, were favoured by the periods after the end of monsoon and end of post monsoon, respectively, the former being capable of tolerating higher differences in the water quality parameters. Q mode factor analysis has grouped the 12 copepod species into two significant factor groups containing the species *A. Sewelli, P. Annandelli* and *Oithona*

Table 4: The optimal regression model for predicting the copepod abundance at different stations in the Bhayander area (Parameters given in bold are limiting parameters).

Station	Parameters	Equation	$F_{(10,4)}$ ratio (V.E. %)	Remarks
Bhayander creek, B1	T, SS, NO_3, NH_4	$Z= 1.6607\text{X}10^{-5} + 27.8876T + 41.8876SS - 88.5057NO_3 -10.6209NH_4 + 1.9012(T*SS) - 37.8690(T*NO_3) + 51.5971(T*NH_4) - 24.0778(SS*NO_3) + 4.0673(SS*NH_4) + 16.7075(NO3*NH4)$ **NO_3** > $T*NH_4$ > NO_3*NH_4 > **$SS*NO_3$** > **$T*NO_3$** > SS > $SS*NH_4$ > **NH_4** > T > SS	3.1763 (60.86)	P<0.05
Bhayander reservoir, B2	S, DO, NO_3, NO_2	$Z=4.9470\text{X}10^{-5} -8.1892S – 19.9129DO + 33.8617NO_3 +5.1050NO_2 +2.3744(S*DO) + 23.8598(S*NO_3) – 12.6587(S*NO_2) – 11.8478(DO*NO_3) – 21.4203(DO*NO_2) +20.9088(NO_3*NO_2)$ NO_3 > $S*NO_3$ > **$S*NO_2$** > **$DO*NO_2$** > **$DO*NO_3$** > NO_3*NO_2> **DO** > **S** > NO_2 > S*DO	11.9354 (88.66)	P<0.01
Bhayander reservoir, B3	S, SS, PO_4, NO_2	$Z=6.1533\text{X}10^{-5}+4.5012S – 0.6386SS + 25.4494PO_4 – 78.0870NO_2 – 3.2501(S*SS) – 1.2211(S* PO_4) – 8.1167(S* NO_2) + 31.5009(SS* PO_4) – 6.2061(SS* NO_2) +13.8422(PO_4*NO_2)$ **NO_2** > $SS*PO_4$ > PO_4*NO_2 > PO_4 > **$SS*NO_2$** > **S*NO2** > S > **S*SS** > **$S*PO_4$** > **SS**	8.1268 (83.58)	P<0.01
Bhayander condenser, B4	pH,SS, PO_4, NH_4	$Z= - 4.2149\text{X}10^{-6} + 10.0017pH + 51.5371SS – 12.3211PO_4 – 292.8298NH_4 + 1.7055(pH*SS) -57.6394(pH*PO_4) + 2.3713(pH*NH_4) +295.1848(SS*PO_4) +3.4177(SS*NH_4) + 3.4871(PO_4*NH_4)$ **NH_4** > $SS*PO_4$ > **pH*PO4** > SS> **PO_4** > $SS*NH_4$ > PO_4*NH_4 > $pH*NH_4$ > pH*SS >pH	14.3467 (90.51)	P<0.01
Bhayander crystalliser, B5	T, pH, S, NH_4	$Z= - 7.712410^{-6} + 152.7609T + 98.7847pH – 91.0627S – 284.6085NH_4 – 2.5154(T*pH) – 223.562(T*S) + 17.8503(T*NH_4) +45.6056(pH*S) + 65.0896(pH*NH_4)$ **NH4** > S*NH4 > **S** > pH*NH4 > pH*S >T*NH4 > T >**T*S** > pH > **T*pH**	11.9713 (88.69)	P<0.01

brevecornis in cluster 1, and *P. tollengerae* and *Callanoid sp.,* in cluster 2 which are clustered at more than 40 -60% similarity by the Bray Curtis similarity clustering technique (Table 3 and Figure 4D). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated phosphate and ammonia to be the limiting factors whereas pH and suspended solids to be controlling factors for copepod abundance at condenser area (Table 4).

At B5, copepods were present only from July to November 1991 and in July 1992, the percentage composition varied from 11.3 in August to 100 in October and November (av. 80.3%). The copepod population ranged from 382–64648 inds./m^3 at B5 during August and July 1991 with average population of 8847 inds./m^3. Still lower variations were observed for the species characteristics distribution in this station with comparatively least value for the niche breadth for all the species. R-mode analysis is not applied due to few number of months. Q-mode factor analysis has grouped the twelve copepod species into 2 clusters containing (1) *Oithona brevecornis, P. annadalei* and *A. sewelli* in cluster 1, and *Bestiolina similis*, and *Paracalanus crassirostris* in cluster 2 at 50 -60% similarity level (Table 3 and Figure 4E). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated salinity and ammonia to be the limiting factors whereas Temperature and pH to be controlling factors for copepod abundance at crystalliser area (Table 4).

On comparing B1 to B5, richness factor decreases from B1 to B3 and then increases at B4 and B5. Diversity index and evenness are maximum at B4. Dominance factor is highest in B2 and lowest in B1, species concentration factor is highest in B1 and B4.

Seasonal variations: Out of 20 species recorded from the creek (B1), only 12 were noticed during pre-monsoon period. *Acartia southwelli* dominated with a contribution of 94.1%. Percentage contribution of the other species viz. *Acartia spinicauda* (1.9%), *Acartiella tortaniforsis* (0.1%) and *Acartia tropica* (0.5%) were low during this period. The number of species recorded during the monsoon period was 13. Of these, *Oithona brevicornis* formed 62.2%, followed by *Bestiolina similis* (29.5%) and *Paracalanus crassirostris* (4.4%). Only 7 species were recorded during the post-monsoon period. *Pseudodiaptomus ardjuna* and *Oithona similis* dominated the group during this season forming 35.7% and 32.7% of copepod. Out of the 20 species recorded from the Bhayander creek only 3 species i.e. *Acartia spinicauda, Bestiolina similis* and *Pseudodiaptomus ardjuna* were noticed throughout the year. The prevalence of species *Acartia southwelli* and *Mesochra* sp. was restricted to pre-monsoon season. *Acartiella keralensis, Oithona similis* were noticed only during post-monsoon, while *Canthocalanus pauper, Acartia tropica, Paracalanus crassirostris and Oithona brevicornis (Oithona breves)* were noticed during monsoon months.

Of the 19 species encountered from the reservoirs (B2 and B3), only 10 species were collected during pre-monsoon. *Acartia southwelli* dominated the group (60.7%) followed by *Oithona similis* (13.1%) *Pseudodiaptomus binghami malayalus* (*Pseudodiaptomus sp.*) (10.4%), *P. ardjuna* and *P.annandalei* 6.7% each. *Oithona brevicornis* formed 6.7% and *Pseudodiaptomus annadalei* 4.2%. Rest of the species were noticed in <1% of the copepod population. Fourteen species were noticed during the post monsoon period. *Acartia tropica* dominated with a contribution of 57.7% followed by *Acartia southwelli* 38.4% while *Oithona brevecornis* contributed only 5.1%. *Acartia southwelli*, *Acartia plumosa, Bestiolina similis*, *Paracalanus crassirostris, Pseudodiaptomus annadalei, P. ardjuna, Mesochra sp.* and *Oithona similis* were noticed throughout the period of observation irrespective of seasons. Seasonal variation was very clear for *Acartia southwelli*, having maximum percentage contribution during pre-monsoon and minimum during monsoon period.

In the condenser (B4), out of 12 species identified only 5 were noticed during pre-monsoon period. *Acartia southwelli* formed 96.2% of copepod density. A Maximum number of 9 species was recorded during the monsoon period. *Pseudodiaptomus annadalei* dominated the group contributing 30.8%. During the post-monsoon period, only 5 species were recorded. The major contribution was that of *Mesochra* sp. (93.6%) followed by *Bestiolina similis* (4.8%) and *Oithona similis* (0.9%). On the whole, monsoon season recorded the highest copepod population as well as the maximum number of species. *Acartia southwelli* and *Mesochra sp.* contributed 90% to copepod population during pre-monsoon and post-monsoon respectively. But during monsoon the percentage contribution of 12 species varied from 0.6 to 30.8%, the maximum being that of *Pseudodiaptomus annadalei* and minimum being that of *Mesochra sp.* In crystallizer (B5), copepod fauna was completely absent during pre-monsoon. During monsoon period out of 12 species recorded *Mesochra* sp. contributed 56.9%, *Oithona similis* 26.8% and *Acartiella sewelli* 9.5%. During post-monsoon only 2 species, *Acartia tropica* (17.1%) and *Oithona similis* (82.9%) were noticed in crystallizer. In general, in the crystallizer in the Bhayander salt pan region *Mesochra* sp., *Oithona similis, and Acartia tropica* (*Acartia sp.* In Figure 4E) thrived well.

Thane system

Community structure of copepod: A total of 18 species belonging to 15 genera of copepods were recorded from Thane system. Copepod species present in each station (T1-T5) are given in Figure 4. At T1, 15 species and at T2, 11 species were recorded. *Oithona similis*, *Acartia kerolensis*, *Mesochra* sp. and *Oithona brevecornis* were abundant. *Bestiolina similis* was also observed from T1. Species decreased to 13 in T3 compared to T1, *Cyclopoid* sp., *Oithona brevecornis, Oithona similis* and *Mesochra* sp. being the abundant species. Meanwhile, 10 species were encountered at T4 and 9 at T5; *Oithona similis*, *Oithona brevecornis*, *Cyclopoid sp.*, *Mesochra sp.* and *Paracalanus crassirostris* were the most common species, but at T5 unusual congregations of *Oithona similis* (Oithona sp. 2 in Figure 4J) (776000 inds./m^3) were found during December 1991 contributing to 98.8% of total copepod population.

Distribution and diversity: At T1, contribution of copepod population to total zooplankton ranged between 26.5% (May 1991) and 99.9% (July 1992) with an average of 89.5%. Copepod population varied between 21 and 86988 inds./m^3 (av. 15249 inds./m^3). Species richness varied between 0.73 (June) and 3.81 (October) with average richness value of 2.15 and relatively lower variation (34.84%). Species diversity index was high (1.04) on the average, with lesser variation, 43.52%. Species richness is comparatively low (0.74) with high variation (67.18%). Dominance factor was highest in June (1.22) and lowest (0.02) in July. *Oithona similis* (5.42), *Acartia spinicauda* (3.61) and *Bestiolina similis* (3.47) have high niche breadth. At T1, three statistically significant groups of months were obtained forming the differential factor groups explaining a major part of the temporal variability in the copepod distribution. The first group of months formed the major part of the study period: May - July and November and December of 1991 and January, May and June of 1992, which supports *Oithona similis* to a great extent. Factor group 2 was constituted by the months of February, April and July of 1992 when *Cyclopoid* sp. occurred relatively in large quantities. Factors 3–5 were dominated by *Bestiolina similis*, *Mesochra* sp. and *P. crassirostris* and explained variability were 91.7%, 91.2% and 67.9%, respectively. Regarding the groups of species, Q-mode analysis separated the 15 species into 3 distinct clusters at 50-70% similarity level, of 2 species each: (1) *Acartia spinicauda* and *Mesochara sp*., (2) *Acartia tropica, Pseudodiaptomus ardjuna* and (2) *Paracalanus crassirostris* and *A. keralensis* (Table 3 and Figure 4F). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated salinity to be the limiting factor whereas nitrate, temperature and dissolved oxygen to be the controlling factors for copepod abundance at Thane creek area (Table 5).

Copepod contribution to total zooplankton at T2 varied from 53.2 (July) to 100% (av. 94.5%). Copepod population at T2 fluctuated between 25 and 48000 inds./m^3 (av. 14385 inds./m^3). At this station the Margalef's index of richness showed an average of 1.14 and seasonal variations of 38.28%. The highest richness was 1.81 (May) and the lowest in 0.49 (September). Shannon Weaver diversity function was minimum in June (0.006) and maximum in May (1.44) with moderately high variation (60.73%). Heip's evenness index was on the average 0.80, with high variation 72.39%. Regarding the dominance factor, there is only very little indication of dominance of species. Highest dominance, 1.01 was in June and lowest in July (0.004). The species concentration factor, on the other hand took an inverse trend. The eleven species were distributed with high niche breadth: (2.98) for *Acartia southwelli*, (2.97) for *Oithona brevecornis* and (2.67) for *Oithona sp*. Maximum niche breadth (3.93) was noticed for *Mesochra* sp. At T2 the study period was divided into 2 ecologically important differential factors containing the periods, November and December of 1991, March, May and June of 1992 in which *Mesochra* sp. were very dominant, and *Oithona similis* in May, June, August and October of 1991. *A southwelli*, *Oithona brevecornis*, *P. adjuna* and *Harpacticoids sp*. dominated in this region. The months included in factor group 1 indicated that ammonia is not the controlling factor for *Mesochra sp.* May, June, August and October 1991 constituting factor 2, indicated that low ammonia is a supporting factor for *Oithona similis.*

Distribution of *A. southwelli*, during September 1991 and February 1992, *O. brevecornis* during January and July 1992, and *P. adjuna* during July 1991 and occurrence of *Harpacticoids sp*. during April 1992 do not add significantly to the conditions prevailing during the study period so as to describe the copepod distribution. Only 11 copepod species were obtained in this station and Q-mode analysis divided them into 3 factor groups of which the factor 1 containing *Kelleri sp.* and *Harpacticoids sp.* at 60% similarity level, factor 2 with *Paracalanus crassirostris* and *Pseudodiaptomus ardjuna* at 45% association level and factor 3 constituted by *A. Southwelli* and *Oithona brevecornis* which are the indicator species of this station (Table 3 and Figure 4G). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated nitrite to be the limiting factor whereas nitrate, phosphate and temperature to be the controlling factors for copepod abundance at Thane reservoir area (Table 5).

At T3, percentage of copepods to total zooplankton varied from 88.2 in July 1991 to 100 in most of the other months (av. 98.4%). Variation in copepod population was from 69–308893 inds./m^3 (av. 41389 inds./m^3). Species richness was maximum (2.3) in November and minimum (0.5) in May 1992. Average uniformity in the distribution was less than that of T2, but greater than that of T1 with high variation of 70.4%. Species diversity did not differ much from that of T2 but was lower than that of T1 (average 0.73). High dominance (1.01) was observed with variation of 65.5%. The highest dominance (2.45) was observed in July 1991 and the lowest (0.008) in July 1992. Species concentration factor was less (0.29) than that of T1 and T2. Species niche breadth was maximum (4.10) for *Oithona similis*. and minimum (1.14) for *Acartia southwelli*. R-mode analysis distinguished two sets of differential periods, namely May,

Table 5: The optimal regression model for predicting the copepod abundance at different stations in the Thane saltpan area (Parameters given in bold are limiting parameters).

Station	Parameters	Equation	$F_{(10, 4)}$ ratio (V.E. %)	Remarks
Thane creek, T1	T, S, DO, NO_3	$Z= 5.2015X10^{-6} + 30.8246T – 189.4520S +164.7025DO + 126.2033NO_3 – 0.3867(T*S) + 108.7686(T*DO) – 143.3625(T*NO_3) – 90.5018(S*DO) + 28.3844(S*NO_3) + 5.8844(DO*NO_3)$ $\mathbf{S*DO >} NO_3 > \mathbf{S} > T*DO > \mathbf{T*NO_3} > DO > S* NO_3 > DO* NO_3 > T > T*S$	5.4784 (76.18)	P<0.05
Thane reservoir, T2	T, PO_4, NO_3, NO_2	$Z= - 4.8228X10^{-5} +1.6392T + 69.1379PO_4 + 50.6466NO_3 – 241.8328NO_2 – 0.0509(T*PO_4) – 47.4305(T*NO_3) – 34.5193(T*NO_2) + 158.1284(PO_4*NO_3) – 2.1845(PO_4*NO_2) +11.4953(NO_3*NO_2)$ $\mathbf{NO_2} > PO_4*NO_3 > \mathbf{T*NO_2} > NO_3 > PO_4 > \mathbf{T*NO_3} > NO_3*NO_2 > \mathbf{PO_4* NO_2} > T > \mathbf{T*PO_4}$	16.0650 (91.50)	P<0.001
Thane reservoir, T3	pH, S, DO, NO_2	$Z=2.0718X10^{-5} – 23.9566pH – 97.9240S + 213.4492DO – 25.5466NO_2 – 0.01684(pH*S) + 115.6086(pH*DO) – 184.5647(pH* NO_2) – 24.3902(S*DO) – 20.3912(S*NO_2) +28.8960(DO*NO_2)$ $pH*DO > \mathbf{S} >DO > pH*NO_2 > DO*NO_2 > \mathbf{S*NO_2} > \mathbf{NO_2} > \mathbf{S*DO >pH >pH*S}$	8.1268 (83.58)	P<0.01
Thane condenser, T4	S, SS, PO_4, NO_3	$Z=6.9385X10^{-5} – 3.6813S + 2.0394SS + 5.9882PO_4 + 1.1062NO_3 + 0.6960(S*SS) +0.6779(S*PO_4) – 2.8534(S*NO_3) +1.2638(SS*PO_4) – 0.7705(SS*NO_3) – 2.2688(PO_4*NO_3)$ $\mathbf{S} > \mathbf{PO_4*NO_3} > \mathbf{S*NO_3} > PO_4 > S*PO_4 > SS >\mathbf{SS*NO_3} > SS*PO_4 > NO_3> S*SS$	9.26 (85.51)	P<0.01
Thane crystalliser, T5	pH, S, PO_4, NO_2	$Z= 1.5023X10^{-5} + 7.1080pH + 19.2114S – 105.7036PO_4 – 41.0037NO_2 – 0.2281(pH*S) – 24.0837(pH*PO_4) + 94.5106(pH*NO_2) +42.9811(S*PO_4) + 7.9918(S*NO_2)$ $\mathbf{PO_4} > pH*NO_2 > \mathbf{NO_2} > S*PO_4 > \mathbf{pH*PO_4} >S > S*NO_2> PO_4*NO_2 > pH > \mathbf{pH*S}$	51.7977 (97.32)	P<0.001

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June, and November of 1991 with abundant distribution of *Oithona similis* and Factor 2 containing the periods, September 1991, June and July of 1992 and July of 1991which are survived by *Cyclopoid sp.* Distribution of these two species indicates the changing environment at this station. The 2 species, *Acartia tropica and Acartia spinicauda* out of the 13 species were linked at 50% similarity and these were the indicator species' distinguishing this station from the rest of the area (Table 3 and Figure 4H). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated salinity, nitrite and pH to be the limiting factors whereas dissolved oxygen to be the controlling factor for copepod abundance at Thane reservoir area (Table 5).

At T4, the crystalliser was survived with 10 copepod species, varying between 86.2% in July 1991 and 100% in most of the other months (av. 98.5%). Monthly fluctuation in copepods was from 56 to 130358 inds./m^3 (av. 20922 inds./m^3). The average species richness factor was 0.89 with high seasonal heterogeneity (79.91%). Maximum richness (2.14) was obtained in August. Species diversity was very low throughout the study period, except during August (2.15) and October (2.35), with a high seasonal variation (74.03%). Species dominance was a highly fluctuating characteristic with the highest dominance of 0.92 in July. Species concentration was very low, 0.27 with a high variability of 74.03%. Only moderate values were present for species niche breadth of 2.58 for *Oithona similis* and 2.72 for *Mesochra* sp. R-mode analysis divided the study period into three statistically significant groups of months namely May 1991, January and March of 1992 dominated by *Mesochra* sp. Factor group 2 identified by the months of July and December of 1991 is survived by *Oithona brevecornis.* Three groups of specific species of this environment having high similarity (40-70%) are (1) *Paracalanus crassirostris*, *Oithona similis, (2) Acartia spinicauda*, *Bestiolina similis* and (3) *A. sewelli* and *Oithona brevecornis* (Table 3 and Figure 4I). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated salinity to be the limiting factor whereas suspended solids, phosphate and nitrate to be the controlling factors for copepod abundance at condenser area (Table 5).

The contribution of copepod at T5 ranged between 23.6% in August and 100% in July both in 1991, 1992, while it was in September, October and December 1991 (av. 88.9%). Copepods were not recorded from st. 5 during May and June 1991 and January to June 1992. The population varied from 61 to 776000 inds./m^3 and was mainly constituted by the nauplii of *Oithona* (av. 60047 inds./m^3). Species evenness index was moderately high with 50.9% variation. Shannon Weaver diversity function was almost uniform except during September (2.2) with a variation of 51.8%. Seasonal variation regarding Pielou's dominance index was almost equal in all the months except for the high value of 2.18 obtained during August. Species concentration factor (0.5) in T5 was the highest. In T5 only *Acartia sewelli* showed a niche breadth of 2.5. Species obtained at this station were clustered into 2 highly associated clusters, (1) *Acartia tropica*, *Mesochara sp.* and *Oithona bervecornis* formed at 50% similarity level and (2) *A. Sewelli*, *Harpacticoids sp.*, formed at 60% similarity level (Table 3 and Figure 4J). Step up multiple regression analysis applied on standardised log transformed values of copepod density and log transformed values of water quality parameters delineated phosphate and nitrite to be the limiting factors whereas pH and salinity to be controlling factors for copepod abundance at Thane crystalliser area (Table 5).

Seasonal variations: In general, the copepod population in Thane salt pan area was very high during monsoon compared to the pre-monsoon and the post monsoon periods. A total of 18 species were encountered in this salt pan. Out of this, 15 species were noticed in the creek, 11 and 13 in the 2 reservoirs, 10 in the condenser and 9 in the crystallizer. In the creek, *Bestiolina similis, Acartia spinicauda, Oithona similis, Cyclopoid sp., Mesochra sp.* were noticed throughout the period. In the reservoir *Acartia tropica, A. southwelli, Oithona similis, O. bervecornis, Cyclopoid sp., Mesochra sp.* and *Harpacticoids sp.* were seen during all the three seasons. In the condenser, only *Oithona similis* and *Mesochra sp.* were recorded throughout the year, whereas in the crystallizer copepods were absent during the pre-monsoon period. *Oithona similis* was the common species occurring throughout the year in all the stations. *Canthocalanus pauper, Eucalanus subcrassus, Centropages dorsispinatus, Euterpiina acutifrons* and *Kelleria sp. s*howed rare occurrence in lower percentage during different seasons at the Creek. *Cyclopoid sp.* dominated the area with varying percentage contribution of 3.2 to 85.0. *Mesochra sp.* was common but the percentage contribution was low in the creek though increased in the other stations.

The copepod abundance was transformed using a fourth root transformation,

$Y=(X+1)^{0.254}$, that is $Y=(X+1)^{1/4}$

P<0.05 and p=0.254 was obtained as the coefficient for optimal transformation using 2 way Tuckey's test of additivity [12] for the species abundance. No significant difference was noted in copepod species abundance between Bhayander and Thane stations ($F_{(9, 2898)}$ <1.88, P>0.05). However, a significant difference appeared between species ($F_{(23, 2898)}$ =22.0218, P<0.01). In the case of months, the difference was not high (P>0.05). Species-wise difference showed significant station - species interaction ($F_{(207, 2898)}$ =2.7401) and species - months interaction ($F_{(322, 2898)}$ =2.1084), (P<0.01). Seasonal differences were more or less uniform in all the stations (P>0.05). The 3 way ANOVA, repeated for the Bhayander and Thane creek separately, resulted in similar observations with significant species-wise difference ($F_{(23,1288)}$ >10.22), high station - species interaction ($F_{(92,1288)}$ >1.97) and high species–months interaction ($F_{(322,1288)}$ >1.39), (P<0.01). This analysis again reveals that the Thane creek shows a distinct feature than the Bhayander creek based on copepod species abundance.

Discussion

Wide fluctuations in environmental factors play a main role in the survival of the plankton community. Water quality parameters indicated well-defined variation between the creek and salt pans. There was gradual increase in temperature from the creek towards the salt pan due to shallowness and stagnant nature of the water body. The relatively higher level of salinity at Thane creek could be attributed to the freshwater influx and input of industrial effluents [28]. In the salt pans salinity is the major factor which influences the distribution of flora and fauna. In the Thane salt pan system the range in salinity was 3.3–344.6 whereas in Bhayander salinity varied from 1–360.7. The observed salinity range at Bhayander and Thane system is comparable to that reported from Vadala (0–320) by Ansari [29] and from Muland salt pan (35–310) by Deshmukh [30]. The increase in salinity from reservoir to salt pan can be attributed to the high rate of evaporation. Nutrients indicated wide fluctuations and the trend is comparable at both the systems. Concentration of nutrients especially nitrate was very high at the creek stations due to influx of waste water. The prevailing environmental conditions of the salt pan systems are unique and both systems have emerged as independent systems maintaining their identity.

Copepods were the most dominant group of zooplankton both at creek and salt pan systems. In the creek system of Bhayander (17–10280 inds./m^3 (av.1758 inds./m^3) and Thane (21–86988 inds./m^3 (av.15249 inds./m^3) the population density of copepods varied enormously indicating a trend very similar to zooplankton population, with >8 times higher numerical abundance of copepods at Thane as compared to Bhayander. The copepods have been reported as the predominant group in the near shore waters of Mumbai [28,31,32] and off the Konkan Coast [33,34]. In the present study, the observed numerical contribution (94–97%) of copepods to the total zooplankton of the Thane and the Bhayander systems was quite high as compared with the contribution of copepods in the Dharamtar creek (71.8%), Cochin backwaters (79.3%) and Vellar estuary (91.0%) as reported by Tiwari and Madhupratap [35,36] and Subbaraju and Krishnamurthy [37], respectively. According to Millar [38], higher densities of copepods result from a succession of several discrete generations. It would appear that within the salt pan system only some groups of zooplankton could thrive well leading to limited competition and this must have further favoured the abundance of copepods. Seasonally, the peak value for copepods was observed during monsoon at both the creek systems. Bal and Pradhan [39] have reported maximum population of copepods during monsoon (July) from the Mumbai harbour regions while Gajbhiye [40] has recorded maximum density during October to November for the coastal waters of Mumbai.

The copepod population increased from creek to the salt pan system by a factor of 1:17 and 1:10 respectively for Bhayander and Thane. The regional difference in distribution of copepods was significant. The observed ratios for creek: reservoir: condenser: crystallizer was 1:15:32:5 and 1:2:1:34 at Bhayander and Thane, respectively. A factor of 1:32 and 1:34 was noticed from creek to condenser (Bhayander) and creek to crystallizer (Thane) due to swarming of *Mesochra* sp and *Oithona* sp., respectively.

Annually, the copepod population in the reservoir of both the systems were almost comparable whereas the condenser at Bhayander sustained 25 times higher population counts as compared to Thane. Reservoir and condenser showed peak values during the monsoon period at the Thane system while in the Bhayander system the peak value was observed in the post monsoon period. Annually, crystallizer sustained nearly 60 times more population (526723 inds/m^3) in Thane as compared to Bhayander (8847 inds./m^3). In the present study, the creek and salt pans at Bhayander and Thane exhibited variation in composition and abundance of copepod species. In general, the creek and reservoir had a higher abundance of copepods than the condenser and crystallizer, both at Bhayander as well as Thane. In the Bhayander creek the numbers of species recorded were 20 in the creek, 19 and 16 in the reservoirs, and 10 each in the condenser and crystallizer. In the Thane system, the numbers of species recorded were 15, 11, 13, 10 and 9 in the creek reservoirs condenser and crystallizer respectively. In general, the Bhayander system was found to be high in diversity compared to the Thane system. The calanoid copepods were the dominant component in the creek and reservoir at Bhayander. But cyclopoids and harpacticoids dominated at the creek and reservoir of Thane. Cyclopoids were also found in swarms in shallow coastal waters. Both harpacticoids and cyclopoids were tolerant to wide fluctuations in salinity.

The steady reduction in the number of species from 20 in the creek to 16 in the reservoir and to 10 each in the condenser and crystalliser, showing almost 50% reduction in the species diversity from creek to crystallizer. *Canthocalanus pauper* was represented only in the creek during monsoon in very low percentage (< 0.1%), *Eucalanus subcrassus* was noticed in the creek and reservoir during the pre-monsoon and the monsoon periods. *Paracalanus crassirostris* was sparsely represented during certain months. *Bestiolina similis* was present in all the stations and seasons, except in the crystallizer during pre-monsoon and post-monsoon, showing maximum percentage during monsoon in the creek. *Centropages dorsispinatus* and *Pseudodiaptomus tollengerae* occurred sparsely in the area studied. *Pseudodiaptomus ardjuna* was present throughout the period of observation in the creek and reservoir but was absent in the condenser and contributed very low percentage in the crystallizer. Maximum concentration was noticed in the creek during the post monsoon period. *P. annadalei* showed its maximum contribution in the condenser during monsoon. *Pseudodiaptomus aurivilli* and *Acartiella tortaniforsis* were observed only from the creek during the pre-monsoon and the monsoon periods in very low percentages. *Pseudodiaptomus binghami malayalus* was present only in the reservoir during pre-monsoon and post-monsoon whereas *Acartiella keralensis* showed its presence in the creek only during post-monsoon. *Acartia southwelli* peaked during pre-monsoon from the creek to condenser, but was totally absent in the crystallizer. The species was not recorded from creek during the monsoon and the post monsoon periods. *Acartia tropica* showed marked seasonal variations, in the reservoir with highest percentage during the post monsoon period. In the condenser, the species was present in moderate percentages during monsoon whereas in the crystallizer it showed high percentage during post-monsoon but, low during monsoon, and was absent during pre-monsoon. *Acartiella sewelli* was observed from the reservoir and crystallizer during post-monsoon and monsoon, respectively. *Oithona brevicornis* was noticed in the creek with very high percentage, but in crystallizer in low percentage during monsoon. *Oithona similis* and *Mesochra* sp. showed marked seasonal variation in the reservoir. In the crystallizer *O. similis* contributed maximum during post-monsoon and was absent during pre-monsoon whereas *Mesochra* sp. was noticed only during monsoon. This species showed maximum contribution in the condenser during post-monsoon. *Oithona hebes* was sparsely represented in all the Sts. except crystallizer. *Cyclops* sp. was present only in the condenser during the monsoon period.

In the salt pans, the ratio of Herbivore: Carnivore: Omnivore varied from 3: 500: 8 to 1: 10,000: 12, 000 at sts. B1, T2 and T4. At other stations, where herbivores were not recorded, the Carnivore: Omnivore ratio ranged between 2: 3 and 84: 1. The temporal and spatial pattern in the abundance of copepods was governed by the environmental factors: temperature, salinity, DO, suspended solids and NH_4 in general. Often copepodites of cyclopoids and harpacticoids exceeded the adults. Regeneration of the population is possible by dormant eggs hatching out in favourable environments. The creeks stations in close proximity to the open ocean sustained highest diversity. The community composition varied with the advancing salinity changes. In the crystalliser where salinity increased rapidly, the harpacticoids flourished well till the water dried up.

The biocenosis of the coastal waters is highly complex. In a study of coexistence of the species inhabiting a particular habitat, the niche requirements are of primary importance. The ecological niche for a species includes an innumerable set of physical parameters as well as biological characteristics. Hence ecological relations of the species should be dealt with in the light of spatial or habitat niche, trophic niche and multidimensional or hyper volume niche [41]. In the present study, the first and last aspects are related to the distribution and coexistence of the species over time and the trophic relations to the mode of feeding. The most important physical property that seems to affect the distribution of copepods in this environment is temperature. The fall in the surface temperature is followed by a change in the species composition. The main reason for different groups of species in the different environments may be that the niche requirements of the different groups do not allow them to coexist. Those species which dominate during the pre and post monsoon periods may shift to the more oceanic regions where the environments does not change markedly and re-establish in the other stations when the environment becomes congenial.

Well defined differences between the creek and the saltpan systems was clearly spelled out through the distribution of various physico-chemical parameters studied. The high variability in the water quality parameters could be attributed to the highly pronounced difference in the salinity distribution right from the creek to the crystalliser. The relatively higher water temperature due to shallowness of the area may be the reason for seasonal variation in the dissolved oxygen level at the condenser and crystalliser. High similarity between the creek environment and the coastal marine system was observed.

An ecological study will be incomplete without an appraisal of the trophic niche of the species. The feeding habits of copepods can be assumed from the nature of the mouth parts [42,43]. Based on the morphology of the mouth parts the copepods of the present study can be grouped as follows.

A certain degree of specialisation in feeding habits is a prerequisite of persistently occurring forms. More over species can change their feeding behaviour either seasonally or through ontogeny [43]. Coexisting forms adjust to the availability of food by adopting different trophic niches. In the coastal association *Eucalanus monachus* an herbivorous species and an omnivorous from *Centropages furcatus* coexist with two predatory species namely *labidocera pectinata* and *Euchaeta wolfendeni.* Similarly in the shelf association an herbivorous copepod *Undinula vulgaris* and two omnivorous species *Temora stylifera* and *T. discaudata* were found to be associated with a carnivorous copepod, *Labidocera acutifrons*. *Cosmocalanus darwini* a filter feeder and a predaceous from *Euchaeta marina* coexist in the offshore association. The surface dwelling forms in coastal habitat are eurytopic enduring wide fluctuations in physical conditions and so cannot be strictly confined to narrow ecological niches. High degree of biological specialisation in a stable environment supports a biologically accommodated community with high species diversity which is often seen in the tropical oceans. The habitat niche in the area covered is severe or unpredictable hence does not favour the existence of a biologically accommodated community. The trophic relations and the reproductive cycles in this biotope may also affect the coexistence of the Calanoida population to a certain extent. The different ecosystems studied have emerged as independent habitats having their own characteristic features, which directly reflected on the community structure of copepods. The salt pans are unique environments where the drastic enhancement in salinity led to decrease in species diversity with predominance of species of *Oithona* and *Mesochra* sp. especially in the crystallizer. In the salt pan, contribution of carnivores and omnivores is high at the condenser and crystalliser. A steady decrease in species richness index as well as diversity is observed from the creek towards the condenser of the salt pan. Species niche breadth is comparatively lower at the condenser and crystalliser as compared to the creek and reservoir.

Shirgur and Deshmukh [44] opined through their study on ecology and fishery potential of the saltpans around Mumbai, that the salt pans supporting dense populations of micro and macro zooplankton, especially the copepod population could very elaborately support aquaculture. Micro-zooplankton density in the Bhayander system [7] has been quantified to be four times more productive than Thane due to which copepod abundance in the former flourished by more than 8 times compared to Thane system. Biju and Panampunnayil [1] observed that Bhayander was more productive than Thane in terms of mysid population density, accounting to nearly 5.5 times more dense. The dissociation between certain copepod species may be due to the mis-match of their environmental preference or inter-specific competition and discontinuity in their distributions.

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