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Seasonal variations in the structure of copepod assemblages in tropical marine and estuarine waters, Coleroon, south-east India

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A twelve-month investigation was undertaken on how copepod community structure varied in relation to environmental factors in the Coleroon estuary, south-east India. Sampling was monthly, from Station 1 in the sea to Station 4 in the Vettar backwaters. Canonical correspondence analysis (CCA) was applied to elucidate the environmental factors affecting the copepod community. A total of 104 copepod species in 38 genera and 26 families were recorded, with the Calanoids, Acartia erythraea *and* Oithona brevicornis *being the most dominant. At all four stations, both these species loaded near the intercept of CCA axes 1 and 2, perhaps reflecting that they were autochthonous. Most species occurred in distinct seasonal patterns. Abundances ranged from* 13×10^3 *to* 215×10^3 *(ind.* m^{-3}*). Coleroon waters showed high diversity (bits/ind.), from 5.29 at Station 3 to 4.97 at Station 4. Abundance correlated positively with temperature and salinity and negatively with rainfall, dissolved oxygen concentration (DO) and pH. Species diversity correlated strongly with abundance* ($P < 0.01$)*. Abundance and diversity were highest during the summer, and both correlated positively with salinity. Temperatures (air and water), salinity, pH and DO varied in the ranges 26–36°C, 25–34.2°C, 9–38, 7.0–8.7 and 3.0–6.8 ml* l^{-1}*, respectively. Nitrate, nitrite, phosphate and silicate (μM) varied in the ranges: 4.7–64.5, 0.4–14.1, 0.2–12.9 and 9.3–148, respectively.*

Keywords: copepods, species composition, community structure, hydrological variables, tropical estuary

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INTRODUCTION

Copepods are the most important secondary producers in aquatic ecosystems as a whole, comprising 90–97% of the total mesozooplankton biomass (Bradford-Grieve *et al.*, 1999). Copepod communities are considered the most important link between phytoplankton and higher trophic levels and are an important determinant of the potential size of a fishery (Uye *et al.*, 2000; Berasategui *et al.*, 2005; Leandro *et al.*, 2007). The distribution and abundance of copepod species are directly and indirectly influenced by environmental factors (Rahman & Verdegem, 2007; Rahman *et al.*, 2010). However, copepod variability is often difficult to relate to these environmental factors because of complex multifactorial influences, particularly in estuaries (Islam *et al.*, 2004; Rahman *et al.*, 2008). Therefore, knowledge of their community structure and distribution patterns in the estuarine environment is essential, both to improve our understanding of their trophic ecology and for successful management of their fisheries (Tseng *et al.*, 2008).

Estuarine copepod communities are believed to be relatively stable inter-annually (David *et al.*, 2005), but to show strong seasonal and spatial dynamics (Winkler *et al.*, 2003). Spatio-temporal variations and habitat types are, therefore, among the most important factors that influence abundance, composition and size structure of estuarine copepods. So it is important to study estuarine copepods at a wide spatial and temporal scale. Temperature, salinity and food supply are among the most important factors that influence the observed spatial and seasonal patterns in demographic variations of copepods (Hassel, 1986), but very little is known about the magnitude of spatio-temporal variation of copepod assemblages in tropical estuarine ecosystems. This information would be very helpful in the designing ecological monitoring programmes for tropical estuarine ecosystems in particular, in order to understand their zooplankton dynamics.

We describe the seasonal variations in the structure of copepod assemblages in the Coleroon estuary, a tropical estuary in south-east India. In this part of India, the four seasons are generally known as post-monsoon (January–March), summer (April–June), pre-monsoon (July–September) and monsoon (October–December). The Coleroon estuary is influenced by intense fresh water discharge during the monsoon, when salinities are lowest (Thillai Rajasekar *et al.*, 2005). As temperature, salinity

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and food supply are different in different locations of an estuary, these studies were conducted at four different locations. The disastrous tsunami of 26 December 2004 (Perumal *et al.*, 2005) hit the coast of the study area between the December and January sampling trips. The coast of Tamil Nadu was severely affected, with thousands of human deaths. Salinification of water sources occurred up to several km from the coast (Perumal *et al.*, 2005), and the topography of the estuary was modified (Kumaraperumal *et al.*, 2007). In a study of planktonic fish larvae in the neighbouring Vellar estuary a few days before and a few days after the tsunami, Sundaramanickam *et al.* (2005) found that fish larval distributions had moved upstream after the tsunami, perhaps having been directly carried there with the ingress of water. The objective of this study was to understand the effects of both seasonal and local geographical variations of physico-chemical parameters in relation to copepod composition and diversity.

MATERIALS AND METHODS

Study area

The river Coleroon, a branch of the river Cauvery, originates from Brahmagiri in the Western Ghats, and after meandering for a distance of over 760 km, forms a very fertile delta in the Nagapattinam District of Tamil Nadu before it empties into the Bay of Bengal at Pazhayaru Harbour (11°21′N 79°50′E) on the south-east coast of India (Figure 1; Table 1). Pazhayaru is one of the three major fishing harbours in Tamil Nadu, contributing a large quantity of seafood to the state. The river Coleroon flows into the Bay of Bengal about 10 km south of Parangipettai. The average width of the Coleroon estuary varies from 420 m at the mouth to 100 m in upstream areas. The average depth near the mouth during high tide is about 7 m, and 1–2 m in the tidal and freshwater zones. The Coleroon estuary includes the Pichavaram mangroves on the northern side and the Buckingham Canal and the Vettar backwaters, two small adjacent drainage channels of paddy fields near the mouth on the southern side. The mouth of the Coleroon River is open to the sea, with a semidiurnal tide. Tidal flushing extends up to a distance of about 15 km upstream.

The sampling stations in the present study are: Station 1, the Bay of Bengal; Station 2, the mouth of the Coleroon river; Station 3, the Coleroon estuary; Station 4, the Vettar backwaters, during one year (April 2004–March 2005). Each sampling station represents a clearly different environment from the others. Station 1 is at the 10 fathom (~18 m) line in the Bay of Bengal. Station 2 is at the mouth of the Coleroon river, which is highly influenced by freshwater inflow during the north-east monsoon season (October–December). The mean salinity was 33. The bottom is sandy. Station 3 is situated near the mouth of the estuary and opposite to the fishing harbour. The bottom is muddy. Station 4 is located about 1.5 km from Station 2 and is highly influenced by freshwater coming through the adjacent Vettar backwaters. The Vettar backwaters also connect with two channels, ‘Chinna Vettar’ and ‘Semmangadu channel’ (Figure 1; Table 1).

Sampling

Surface water and copepod samples were collected monthly from the study area (11°21′N 79°50′E) (Figure 1), always around high water, from April 2004 to March 2005 (Table 2). Samples were taken on 3 December 2004, 23 days before the tsunami, and on 4 January 2005, nine days after.

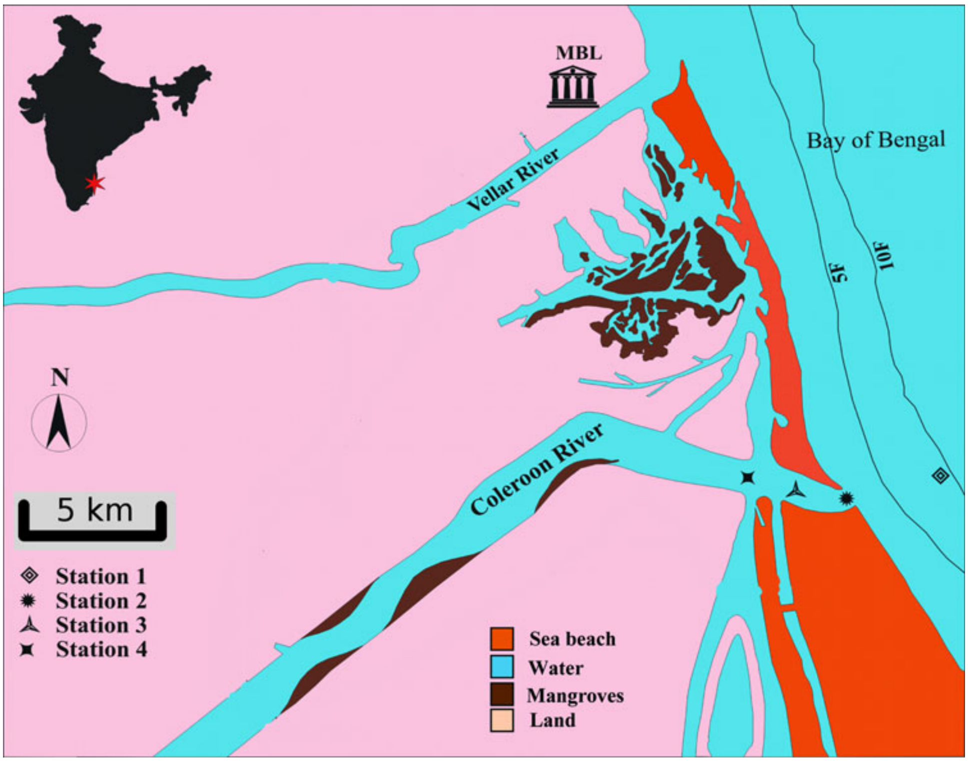

Fig. 1. Map showing the study area.

Table 1. Station locations, depth and characteristic salinity.

Stations	Latitude (N)	Longitude (E)	Depth (m)	Salinity
Station 1	11°21′18.17″	80°15′22.91″	15	35.5
Station 2	11°21′49.50″	79°49′53.89″	7	34.5
Station 3	11°21′35.99″	79°49′33.51″	6	38
Station 4	11°21′37.30″	79°48′59.01″	4	36

Rainfall data were obtained from the office of the Meteorological Department (Government of India) at Coleroon. Air and surface water temperatures were measured using a standard thermometer. Salinity was estimated with a hand refractometer (Atago, Japan) and the pH was measured using an Elico pH meter (Model LC-120). Dissolved oxygen (DO) was estimated by the modified Winkler's method described by Strickland & Parsons (1972). For the analysis of nutrients, surface water samples were collected in polythene bottles and kept in an icebox and transported immediately to the laboratory. The water samples were filtered using a Millipore filtering system (MFS) and the nutrients were analysed according to Strickland & Parsons (1972).

Copepod samples were collected in horizontal hauls from the surface water using a conical net (mouth area 0.25 m^2) made up of bolting silk (mesh size 200 μm) fitted with a calibrated flow meter. Copepod samples were filtered, drained of excess water on absorbent paper and added to a known volume of water to determine the displacement volume. The collected samples were preserved in a 5% buffered formaldehyde–seawater solution, following Goswami (1982). Depending on the size of the sample, aliquots of 5–10% were examined for the enumeration of copepods and their species. Copepods were computed to counts per unit volume of water filtered using the flow meter readings.

Data analyses

Copepod Dominance Index (Y) in each collection has been calculated using the following formulae:

$$Y = \frac{n_i}{N} f_i$$

where n_i is the number of individuals of species i, f_i is the frequency of species i that occurred in a sample and N is the total number of species, the Shannon–Weaver diversity index (Tramer, 1969),

$$H' = -\Sigma;\, p_i \ln p_i$$

where p_i is the number of individuals in the ith species, Pielou's evenness index (Tramer, 1969),

$$J' = H' / \ln S$$

where S is the total number of species and the Margalef species diversity index (Warwick & Clarke, 1995),

$$D_{Mg} = (S - 1) / \ln N$$

where N is the total number of individuals.

Correlation coefficients (r) were calculated between copepod abundance and physico-chemical variables, and one-way analysis of variance (ANOVA) tests were made for hydrological variables in relation to stations and seasons. A suite of statistical analyses carried out using the statistical packages Origin Pro (v.7.5) and SPSS (v.16 for Windows, SPSS, Chicago, IL, USA) to elucidate the variations among the physico-chemical variables.

Canonical correspondence analysis (CCA) was performed to evaluate possible correlations between environmental variables, copepod species and variance by month, using stepwise regression. The CCA was performed using the multivariate statistical software CANOCO routine (v.4.53, Ter Braak, 1986; Ter Braak & Smilauer, 2002) implemented in CANOCO linking copepod communities with environmental variables (rainfall, air temperature, surface water temperature, salinity, pH, DO, nitrate, nitrite, phosphate and silicate). The CCA for all collections was performed on selected species, on the basis of their Dominance Index (Y) and in the light of known environmental data. A Monte Carlo permutation test (unrestricted) was used to determine the significance of species–environment relationships for all the collections at Stations 1, 2, 3 and 4 separately, and the results are given in Table 5.

In the results section below values are expressed as mean ±SD.

Table 2. Sampling season, date, time and state of the tide.

Season	Month	Date	Tide	Station 1	Station 2	Station 3	Station 4
Summer	April, 2004	06/04/2004	High	06:30	07:50	08:35	09:20
	May	06/05/2004	High	07:00	08:25	09:10	09:50
	June	05/06/2004	High	07:20	08:40	09:25	10:10
Pre-monsoon	July	05/07/2004	High	07:30	08:55	09:40	10:25
	August	03/08/2004	High	07:10	08:35	09:25	10:15
	September	03/09/2004	High	07:50	09:10	10:05	10:50
Monsoon (Tsunami, 26/12/2004)	October	03/10/2004	High	07:15	08:35	09:30	10:15
	November	04/11/2004	High	09:30	11:00	11:50	12:30
	December	03/12/2004	High	09:10	10:35	11:30	12:20
Post-monsoon	January, 2005	04/01/2005	High	12:15	13:40	14:30	15:15
	February	03/02/2005	High	12:40	14:05	14:55	15:05
	March	08/03/2005	High	05:15	06:40	07:30	08:15

RESULTS

Physico-chemical variables

Monthly rainfall ranged between 1 mm (post-monsoon season) and 660 mm (monsoon season). No rainfall was recorded during March 2004 and April 2005 (Figure 2A). Air temperature varied from 26°C to 36°C for all the four stations, with values of 29.55 ± 1.48 (Station 2) and 31.26 ± 2.03 (Station 4) (Figure 2B). Surface water temperature varied from 25°C to 34.2°C for all the four stations, with values of 29.25 ± 2.26 (Station 3) and 30.30 ± 2.23 (Station 4) (Figure 2C). Salinity varied from 9 to 38 for all the four stations, with values of 26.72 ± 10.13 (Station 3) and 31.58 ± 3.57 (Station 1) (Figure 2D). pH in water ranged between 7.0 and 8.7 for all the four stations, with values of 7.73 ± 0.42 (Stations 2 & 3) and 7.97 ± 0.30 (Station 4) (Figure 2E). Variation in DO content was from 3.0 to 6.8 ml l^{-1} for all the four stations, with values of 3.74 ± 0.59 ml l^{-1} (Station 2) and 4.99 ± 0.94 ml l^{-1} (Station 4) (Figure 2F). Nitrate varied from 4.7 to 64.5 µM for all the four stations, with values of 16.17 ± 9.29 µM (Station 2) and 25.70 ± 13.05 µM (Station 3) (Figure 2G). Nitrite ranged between 0.4 and 14.1 µM for all the four stations, with values of 2.79 ± 1.86 µM (Station 1) and 5.39 ± 4.64 µM (Station 3) (Figure 2H). Phosphate varied from 0.2 to 12.93 µM for all the four stations, with values of 1.30 ± 0.52 µM (Station 1) and 4.31 ± 4.47 µM (Station 3) (Figure 2I). Silicate ranged between 9.3 and 148 µM for all the four stations, with values of 42.78 ± 42.24 µM (Station 4) and 46.75 ± 45.7 µM (Station 3) (Figure 2J). In relation to the tsunami, the differences between the December and January samples relative to the general seasonal curves showed no striking differences in physico-chemical variables, except for a marked increase in nitrite, phosphate and silicate in October, November and December, associated with lowered salinities during the monsoon.

Species composition and abundance

A total of 104 species of copepods belonging to 26 families and 38 genera were identified at the four stations (Table 3): 65 Calanoid species, 11 Harpacticoid species and 28 Cyclopoid species. From the samples studied, 31 species, (20 Calanoida, six Harpacticoida and five Cyclopoida) were found to be common at all four stations. Inter-station and temporal variations of dominant copepod abundance during April 2004–March 2005 are shown in Figure 3. There was no statistical difference ($P > 0.05$) in copepod abundance between any of the stations, while temporal variation in copepod abundance was significant ($P < 0.05$) (Figure 3). Highest copepod abundance was observed in March, followed by February, January, April, June, December, July, August, May, September, November and October.

Diversity and community structure

Copepod diversity ranged between 4.43 and 5.29 for all the four stations, with values of 4.63 ± 0.18 (Station 4) and 5.10 ± 0.18 (Station 3) (Figure 4). Copepod richness ranged between 2.71 and 7.27 for all the four stations, with values of 3.0 ± 0.16 (Station 4) and 4.41 ± 1.29 (Station 3). Copepod evenness ranged between 0.75 and 0.95 for all the four stations, with values of 0.86 ± 0.04 (Station 1) and

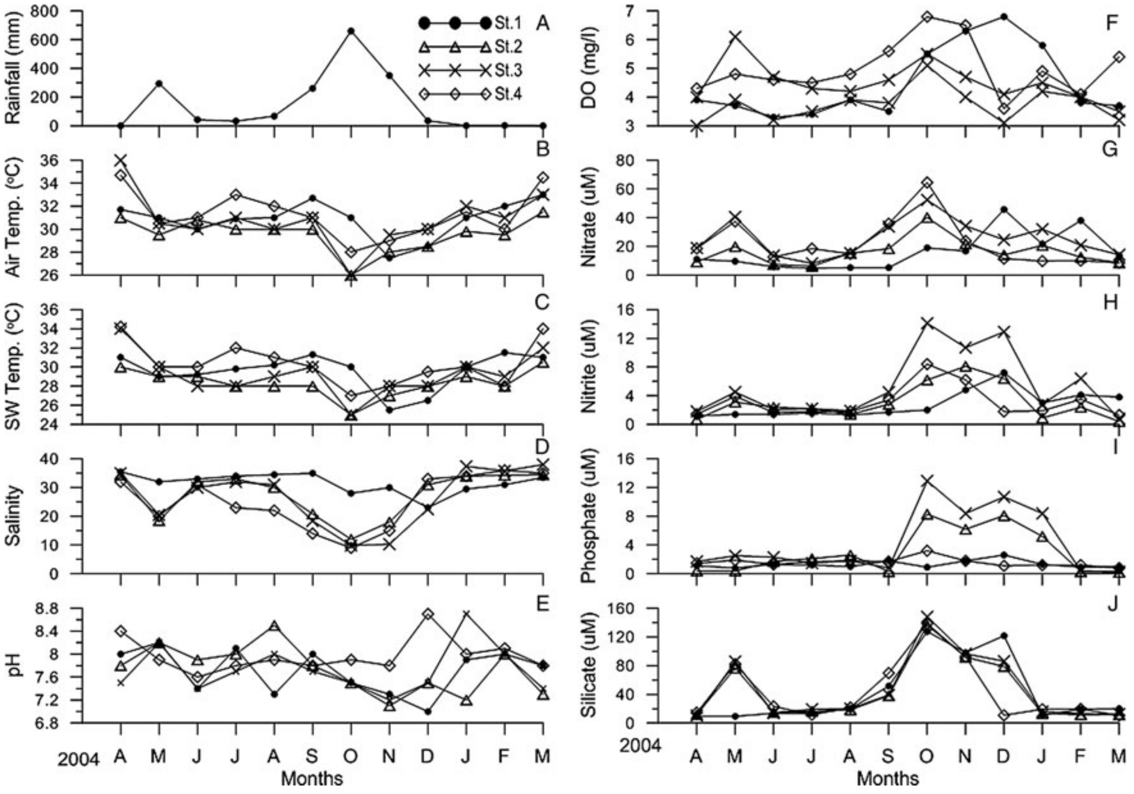

Fig. 2. Monthly inter-station physico-chemical variables during the study period. (A) Rainfall; (B) air temperature; (C) surface water temperature;(D) salinity; (E) pH; (F) dissolved oxygen; (G) nitrate; (H) nitrite; (I) phosphate; (J) silicate.

Table 3. Dominant and common copepod species recorded. (Species number is used in CCA, n_i is species abundance, f_i is species frequency, Y is the Dominance Index). Species with a value of $Y > 0.01$ at any station are highlighted in bold type.

Species	Stn 1 Sp. no.	n_i	f_i	Y	Stn 2 Sp. no.	n_i	f_i	Y	Stn 3 Sp. no.	n_i	f_i	Y	Stn 4 Sp. no.	n_i	f_i	Y
CALANOIDA																
CALANIDAE																
Nannocalanus minor (Claus, 1863)	20	0.013	1.000	**0.0133**	16	0.026	0.833	**0.0217**	26	0.017	1.000	**0.0171**	22	0.019	1.000	**0.0186**
Canthocalanus pauper (Giesbrecht, 1892)	50	0.002	0.500	0.0010	60	–	–	–	73	–	–	–	38	–	–	–
Undinula vulgaris (Dana, 1849)	79	0.001	0.333	0.0002	45	0.004	0.500	0.0019	74	–	–	–	39	–	–	–
U. darwinii (Lubbock, 1860)	46	0.002	0.500	0.0012	61	–	–	–	75	–	–	–	40	–	–	–
Calanus tenuicornis (Dana, 1849)	48	0.002	0.583	0.0011	36	0.005	0.750	0.0036	76	–	–	–	41	–	–	–
C. helgolandicus (Claus, 1863)	43	0.003	0.583	0.0016	53	0.002	0.333	0.0008	77	–	–	–	42	–	–	–
Calanus sp.	86	0.000	0.167	0.0001	55	0.002	0.250	0.0006	78	–	–	–	43	–	–	–
EUCALANIDAE																
Rhincalanus cornutus (Dana, 1849)	30	0.004	0.833	0.0033	62	–	–	–	43	0.003	0.417	0.0013	44	–	–	–
R. nasutus Giesbrecht, 1888	90	–	–	–	63	–	–	–	52	0.002	0.417	0.0007	45	–	–	–
Eucalanus elongatus (Dana, 1849)	19	0.017	1.000	**0.0167**	19	0.019	0.917	**0.0178**	11	0.030	1.000	**0.0300**	21	0.019	1.000	**0.0194**
E. attenuatus (Dana, 1853)	84	0.001	0.167	0.0001	33	0.009	0.583	0.0053	12	0.029	1.000	**0.0288**	24	0.017	1.000	**0.0172**
E. crassus (Giesbrecht, 1888)	54	0.002	0.500	0.0010	25	0.018	0.750	**0.0136**	68	0.001	0.167	0.0001	46	–	–	–
E. subcrassus (Giesbrecht, 1888)	60	0.002	0.417	0.0007	64	–	–	–	79	–	–	–	47	–	–	–
PSEUDOCALANOIDAE																
Calocalanus pavo (Dana, 1849)	35	0.003	0.750	0.0021	65	–	–	–	80	–	–	–	48	–	–	–
PARACALANIDAE																
Paracalanus parvus (Claus, 1863)	6	0.055	1.000	**0.0554**	1	0.070	1.000	**0.0698**	1	0.067	1.000	**0.0672**	7	0.044	1.000	**0.0442**
P. aculeatus Giesbrecht, 1888	38	0.004	0.417	0.0018	66	–	–	–	81	–	–	–	49	–	–	–
Acrocalanus gibber Giesbrecht, 1888	31	0.008	0.417	0.0032	14	0.030	0.750	**0.0223**	18	0.023	1.000	**0.0231**	26	0.016	1.000	**0.0158**
A. gracilis Giesbrecht, 1888	8	0.044	1.000	**0.0439**	8	0.039	1.000	**0.0386**	28	0.015	1.000	**0.0149**	25	0.016	1.000	**0.0163**
A. longicornis Giesbrecht, 1888	63	0.001	0.417	0.0006	39	0.005	0.583	0.0027	24	0.019	1.000	**0.0188**	32	0.006	1.000	0.0062
A. monachus Giesbrecht, 1888	28	0.006	0.667	0.0037	67	–	–	–	82	–	–	–	50	–	–	–
EUCHAETIDAE																
Euchaeta concinna Dana, 1849	58	0.002	0.500	0.0008	68	–	–	–	83	–	–	–	51	–	–	–
E. marina Prestandrea, 1833	2	0.064	1.000	**0.0637**	18	0.021	1.000	**0.0212**	16	0.023	1.000	**0.0232**	2	0.073	1.000	**0.0727**
Euphausia brevis (Hansen, 1905)	91	–	–	–	37	0.005	0.667	0.0035	54	0.002	0.417	0.0006	35	0.003	0.583	0.0017
SCOLECITHRICIDAE																
Scolecithrix danae (Lubbock, 1856)	72	0.002	0.250	0.0004	69	–	–	–	84	–	–	–	52	–	–	–
CENTROPAGIDAE																
Centropages orsinii (Giesbrecht, 1889)	33	0.003	0.750	0.0023	70	–	–	–	62	0.001	0.167	0.0002	53	–	–	–
C. furcatus (Dana, 1849)	59	0.002	0.333	0.0007	38	0.005	0.583	0.0029	42	0.004	0.500	0.0019	54	–	–	–
Centropages **sp.**	66	0.001	0.333	0.0005	9	0.038	1.000	**0.0377**	14	0.025	1.000	**0.0254**	3	0.060	1.000	**0.0602**
C. tenuiremis Thompson & Scott	26	0.008	0.667	0.0051	71	–	–	–	85	–	–	–	55	–	–	–
C. gracilis (Dana, 1849)	37	0.003	0.583	0.0019	72	–	–	–	63	0.001	0.167	0.0002	56	–	–	–
C. elongatus (Giesbrecht, 1896)	49	0.002	0.500	0.0011	73	–	–	–	39	0.008	0.500	0.0041	57	–	–	–
PSEUDODIAPTOMIDAE																
Pseudodiaptomus aurivilli Cleve	40	0.003	0.583	0.0017	35	0.005	0.833	0.0043	71	0.001	0.083	0.0001	58	–	–	–
P. annandalei Sewell	27	0.007	0.583	0.0039	74	–	–	–	30	0.011	1.000	**0.0113**	34	0.009	0.417	0.0037

Continued

Table 3. Continued.

Species	Stn 1 Sp. no.	n_i	f_i	Y	Stn 2 Sp. no.	n_i	f_i	Y	Stn 3 Sp. no.	n_i	f_i	Y	Stn 4 Sp. no.	n_i	f_i	Y
P. serricaudatus (T. Scott)	83	0.001	0.167	0.0001	17	0.022	1.000	**0.0216**	6	0.040	1.000	**0.0403**	1	0.090	1.000	**0.0899**
TEMORIDAE																
Temora turbinata (Dana, 1849)	5	0.056	1.000	**0.0559**	6	0.047	1.000	**0.0473**	23	0.020	1.000	**0.0198**	9	0.039	1.000	**0.0392**
T. discaudata (Giesbrecht, 1889)	80	0.001	0.167	0.0002	27	0.018	0.583	**0.0102**	64	0.001	0.167	0.0001	59	–	–	–
T. stylifera (Dana, 1849)	34	0.004	0.583	0.0022	34	0.006	0.750	0.0045	10	0.032	1.000	**0.0316**	13	0.032	1.000	**0.0316**
ARIETELLIDAE																
Metacalanus aurivilli Cleve	89	0.000	0.167	0.0000	32	0.006	0.833	0.0053	86	–	–	–	60	–	–	–
CANDACIIDAE																
Candacia discaudata A. Scott, 1909	25	0.008	0.750	0.0057	75	–	–	–	87	–	–	–	61	–	–	–
C. bradyi A. Scott	75	0.001	0.250	0.0003	76	–	–	–	31	0.017	0.667	**0.0111**	62	–	–	–
C. pachydactyla (Dana, 1849)	23	0.011	0.583	0.0061	77	–	–	–	88	–	–	–	63	–	–	–
PONTELLIDAE																
Calanopia elliptica (Dana, 1849)	36	0.004	0.583	0.0021	78	–	–	–	89	–	–	–	64	–	–	–
C. aurivilli (Cleve)	64	0.002	0.333	0.0005	41	0.004	0.583	0.0024	90	–	–	–	65	–	–	–
C. minor A. Scott, 1902	85	0.000	0.167	0.0001	58	0.002	0.250	0.0004	35	0.011	0.667	0.0070	66	–	–	–
Labidocera acuta (Dana, 1849)	15	0.028	1.000	**0.0276**	12	0.034	1.000	**0.0338**	4	0.045	1.000	**0.0448**	15	0.027	1.000	**0.0269**
L. pectinata Thompson & Scott	87	0.000	0.167	0.0001	59	0.001	0.250	0.0003	61	0.001	0.167	0.0002	67	–	–	–
L. minuta Giesbrecht, 1889	70	0.001	0.333	0.0004	28	0.011	0.833	0.0094	34	0.017	0.500	0.0083	18	0.023	1.000	**0.0234**
L. pavo (Giesbrecht, 1889)	52	0.002	0.417	0.0010	79	–	–	–	53	0.003	0.250	0.0006	68	–	–	–
L. bengalensis Krishnaswamy	39	0.003	0.500	0.0017	80	–	–	–	91	–	–	–	69	–	–	–
Pontella danae Giesbrecht	17	0.024	1.000	**0.0240**	23	0.016	0.917	**0.0146**	25	0.020	0.917	**0.0180**	5	0.048	1.000	**0.0481**
P. securifer (Brady, 1883)	74	0.001	0.333	0.0004	81	–	–	–	92	–	–	–	37	0.003	0.083	0.0003
P. spinipes (Giesbrecht, 1889)	92	–	–	–	54	0.002	0.333	0.0007	57	0.001	0.333	0.0004	70	–	–	–
Pontellopsis herdmani Thompson & Scott	82	0.001	0.250	0.0001	82	–	–	–	93	–	–	–	71	–	–	–
Pontellina plumata (Dana, 1849)	57	0.001	0.583	0.0009	83	–	–	–	94	–	–	–	72	–	–	–
ACARTIIDAE																
Acartia spinicauda (Giesbrecht, 1889)	13	0.034	1.000	**0.0344**	24	0.024	0.583	**0.0141**	8	0.036	1.000	**0.0355**	20	0.020	1.000	**0.0201**
A. erythraea Giesbrecht, 1889	4	0.061	1.000	**0.0611**	2	0.056	1.000	**0.0560**	2	0.052	1.000	**0.0519**	6	0.047	1.000	**0.0466**
A. centrura (Giesbrecht, 1889)	76	0.001	0.250	0.0003	21	0.015	1.000	**0.0148**	95	–	–	–	73	–	–	–
A. danae Giesbrecht, 1889	7	0.054	1.000	**0.0544**	3	0.055	1.000	**0.0554**	21	0.021	1.000	**0.0209**	8	0.043	1.000	**0.0430**
A. southwelli Sewell	1	0.064	1.000	**0.0637**	10	0.037	1.000	**0.0368**	13	0.028	1.000	**0.0275**	31	0.008	1.000	0.0081
A. negligens Dana, 1849	12	0.039	0.917	**0.0357**	48	0.003	0.500	0.0016	32	0.011	1.000	**0.0108**	23	0.017	1.000	**0.0174**
A. sewelli Steuer	42	0.003	0.583	0.0016	42	0.004	0.583	0.0023	96	–	–	–	74	–	–	–
A. clausi (Giesbrecht, 1889)	81	0.001	0.250	0.0002	57	0.002	0.250	0.0005	70	0.000	0.167	0.0001	75	–	–	–
A. chilkaensis Sewell	73	0.001	0.333	0.0004	52	0.003	0.333	0.0009	60	0.001	0.333	0.0003	76	–	–	–
TORTANIDAE																
Tortanus barbatus (Brady)	77	0.001	0.250	0.0002	84	–	–	–	97	–	–	–	77	–	–	–
T. forcipatus (Giesbrecht, 1889)	67	0.001	0.417	0.0005	44	0.004	0.583	0.0021	98	–	–	–	36	0.003	0.417	0.0014
T. gracilis (Brady)	45	0.002	0.583	0.0014	51	0.003	0.417	0.0011	99	–	–	–	78	–	–	–
HARPACTICOIDA																
LONGIPEDIIDAE																
Longipedia coronata (Claus, 1863)	71	0.001	0.333	0.0004	85	–	–	–	100	–	–	–	79	–	–	–
L. weberi A. Scott	93	–	–	–	20	0.016	1.000	**0.0159**	22	0.021	1.000	**0.0209**	80	–	–	–
ECTINOSOMIDAE																

Microsetella norvegica **(Boeck, 1864)**	21	0.013	1.000	**0.0127**	13	0.031	1.000	**0.0310**	19	0.023	1.000	**0.0230**	19	0.021	1.000	**0.0208**
M. rosea (Dana, 1853)	9	0.040	1.000	**0.0404**	5	0.049	1.000	**0.0489**	9	0.033	1.000	**0.0333**	17	0.024	1.000	**0.0236**
MACROSETELLIDAE																
Macrosetella gracilis (Dana, 1846)	3	0.062	1.000	**0.0616**	15	0.022	1.000	**0.0222**	3	0.047	1.000	**0.0469**	12	0.034	1.000	**0.0345**
Miracia efferata (Dana, 1849)	94	–	–	–	40	0.004	0.667	0.0024	101	–	–	–	81	–	–	–
CLYTEMNESTRIDAE																
Clytemnestra dorsipinnatus	95	–	–	–	46	0.003	0.500	0.0017	47	0.002	0.500	0.0008	82	–	–	–
C. rostrata (Brady, 1883)	29	0.005	0.750	0.0035	49	0.003	0.583	0.0015	59	0.001	0.250	0.0004	83	–	–	–
C. scutellata Dana, 1847	55	0.002	0.500	0.0010	50	0.003	0.500	0.0013	33	0.011	1.000	**0.0106**	29	0.009	1.000	0.0087
TACHIDIIDAE																
Euterpina acutifrons (Dana, 1847)	16	0.027	1.000	**0.0269**	4	0.051	1.000	**0.0508**	27	0.015	1.000	**0.0153**	30	0.008	1.000	0.0084
METIDAE																
Metis jousseaumei (Richard, 1892)	51	0.002	0.500	0.0010	56	0.002	0.250	0.0006	15	0.023	1.000	**0.0235**	16	0.025	1.000	**0.0250**
CYCLOPOIDA																
OITHONIDAE																
Oithona plumifera Baird, 1843	88	0.000	0.167	0.0001	86	–	–	–	69	0.000	0.167	0.0001	84	–	–	–
O. similis Claus 1866 (= *O. helgolandica* Claus)	14	0.032	1.000	**0.0322**	11	0.037	1.000	**0.0366**	7	0.036	1.000	**0.0357**	11	0.036	1.000	**0.0356**
O. rigida Giesbrecht, 1896	18	0.019	0.917	**0.0172**	7	0.040	1.000	**0.0403**	29	0.013	1.000	**0.0133**	28	0.009	1.000	0.0089
O. brevicornis (Giesbrecht, 1891)	10	0.038	1.000	**0.0376**	26	0.013	1.000	**0.0126**	5	0.040	1.000	**0.0405**	4	0.059	1.000	**0.0585**
O. longiramis	61	0.002	0.333	0.0006	87	–	–	–	102	–	–	–	85	–	–	–
O. linearis (Giesbrecht, 1891)	56	0.002	0.500	0.0009	88	–	–	–	48	0.002	0.417	0.0008	86	–	–	–
O. setigera (Dana, 1849)	24	0.012	0.500	0.0059	89	–	–	–	103	–	–	–	87	–	–	–
O. nana (Giesbrecht, 1892)	32	0.004	0.583	0.0025	31	0.008	0.667	0.0056	45	0.003	0.333	0.0009	88	–	–	–
Oithona sp.	22	0.011	0.583	0.0063	90	–	–	–	38	0.007	0.667	0.0047	89	–	–	–
ONCAEIDAE																
Oncaea venusta Philippi, 1843	65	0.002	0.333	0.0005	91	–	–	–	41	0.004	0.500	0.0019	90	–	–	–
O. conifera Giesbrecht, 1891	62	0.002	0.333	0.0006	92	–	–	–	72	0.000	0.167	0.0000	91	–	–	–
CORYCAEIDAE																
Corycaeus danae Giesbrecht, 1891 (= *C. crassiusculus* Dana)	11	0.036	1.000	**0.0361**	22	0.015	1.000	**0.0147**	20	0.022	1.000	**0.0225**	14	0.027	1.000	**0.0272**
C. speciosus Dana, 1849	78	0.001	0.333	0.0002	93	–	–	–	56	0.002	0.250	0.0005	92	–	–	–
C. forcipatus	96	–	–	–	43	0.004	0.500	0.0021	104	–	–	–	10	0.038	1.000	**0.0385**
C. anglicus (Lubbock, 1857)	97	–	–	–	30	0.010	0.667	0.0063	55	0.003	0.250	0.0006	33	0.011	0.417	0.0047
C. ovalis (Claus, 1863)	98	–	–	–	94	–	–	–	51	0.001	0.500	0.0007	93	–	–	–
C. catus F. Dahl, 1894	68	0.001	0.417	0.0005	47	0.003	0.500	0.0017	67	0.001	0.167	0.0001	94	–	–	–
C. gibbula Giesbrecht	99	–	–	–	95	–	–	–	36	0.008	0.833	0.0065	95	–	–	–
Corycella furcifer	69	0.001	0.417	0.0005	96	–	–	–	65	0.001	0.167	0.0001	96	–	–	–
Copilia vitrea (Haeckel, 1864)	44	0.003	0.583	0.0016	97	–	–	–	66	0.001	0.167	0.0001	97	–	–	–
C. mirabilis Dana, 1849	47	0.002	0.583	0.0012	29	0.010	0.833	0.0085	17	0.023	1.000	**0.0232**	27	0.016	1.000	**0.0157**
SAPPHIRINIDAE																
Sapphirina ovatolanceolata Dana, 1849	100	–	–	–	98	–	–	–	49	0.002	0.333	0.0007	98	–	–	–
S. auronitens Claus, 1863	53	0.002	0.583	0.0010	99	–	–	–	44	0.002	0.500	0.0010	99	–	–	–
S. nigromaculata Claus, 1849	41	0.002	0.667	0.0016	100	–	–	–	50	0.002	0.417	0.0007	100	–	–	–
BOMOLOCHIDAE																
Bomolochus sp.	101	–	–	–	101	–	–	–	46	0.002	0.500	0.0009	101	–	–	–

Continued

Table 3. Continued.

Species	Stn 1 Sp. no.	n_i	f_i	Y	Stn 2 Sp. no.	n_i	f_i	Y	Stn 3 Sp. no.	n_i	f_i	Y	Stn 4 Sp. no.	n_i	f_i	Y
CYCLOPIDAE																
Microcyclops varicans (G.O. Sars, 1863)	102	–	–	–	102	–	–	–	40	0.004	0.583	0.0023	102	–	–	–
Mesocyclops leukarti (Claus, 1857)	103	–	–	–	103	–	–	–	58	0.002	0.250	0.0004	103	–	–	–
M. hyalinus (Rehberg)	104	–	–	–	104	–	–	–	37	0.008	0.583	0.0049	104	–	–	–

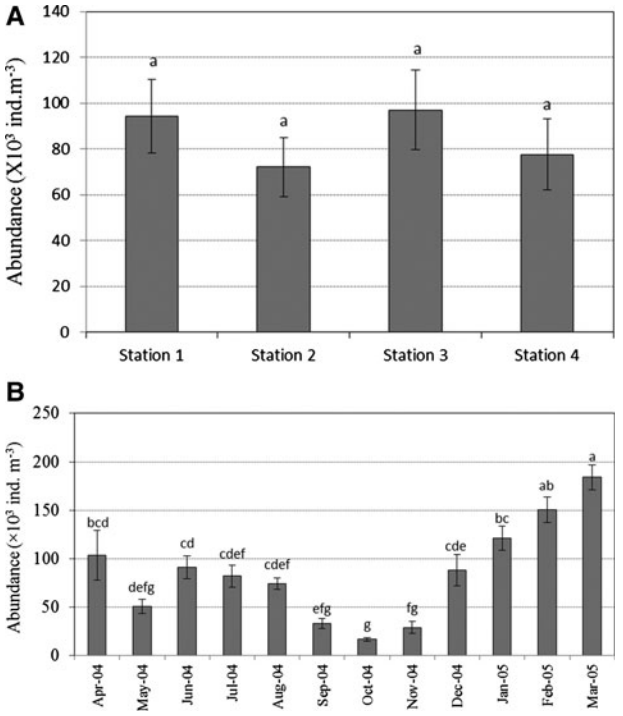

Fig. 3. Inter-station (A) and temporal (B) variations of copepod abundance based on two-way ANOVA. Bars with no letter in common are significantly different based on the Tukey test ($P < 0.05$). Data are mean ± standard error.

0.92 ± 0.01 (Station 3) (Table 4). Finally, overall diversity indices of copepod abundance (ind. m^{-3}), diversity, richness and evenness were: $72 \times 10^3 - 97 \times 10^3$; 4.83–5.36; 3.19–7.68 and 0.79–0.92, respectively.

The results of the multivariate analysis (CCA) for all the stations are shown in Table 5. At Station 1, the first CCA axis initially separated nitrate, pH, nitrite and surface water temperature along with two monthly sampling collections, January 2005 and February 2005 (Figure 5A). On the second CCA axis, the only environmental factor was air temperature along with a single month sampling collection, March 2005. The third CCA axis further separated phosphate, silicate, rainfall and salinity along with six loosely related

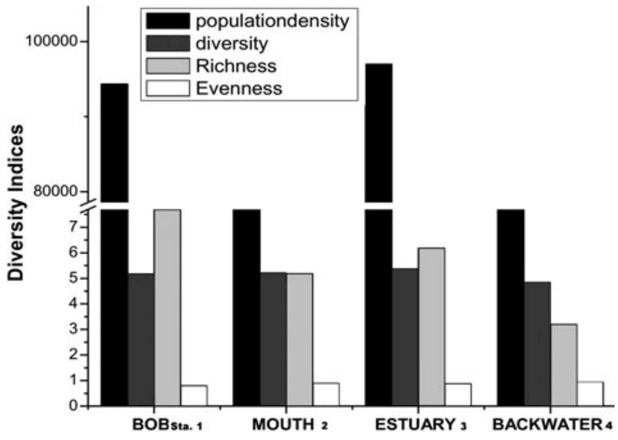

Fig. 4. Station-wise copepod abundance, diversity (Shannon–Wiener diversity index), richness (Margalef's richness) and evenness. BOB, MOUTH, ESTUARY and BACKWATER indicate Station 1, Station 2, Station 3 and Station 4, respectively.

Table 4. Mean diversity measurements for copepod fauna.

	Apr. 2004	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan. 2005	Feb.	Mar.
Shannon–Wiener diversity index H'												
Station 1	4.90	4.65	4.81	4.71	5.01	4.46	4.59	4.56	4.94	5.21	5.19	4.81
Station 2	4.96	4.78	5.00	4.86	5.00	4.78	4.59	4.78	4.86	5.06	5.17	5.08
Station 3	5.09	5.15	5.29	5.24	5.21	4.87	4.70	4.86	5.24	5.15	5.29	5.14
Station 4	4.54	4.55	4.52	4.49	4.50	4.48	4.43	4.80	4.70	4.81	4.88	4.97
Margalef's richness d												
Station 1	7.27	3.60	4.10	3.79	4.83	3.04	3.22	3.13	4.68	5.94	5.54	3.86
Station 2	4.29	3.87	4.30	3.55	4.19	3.15	2.72	3.21	3.34	4.57	4.11	3.71
Station 3	3.62	4.17	4.81	4.73	4.70	4.02	3.36	3.69	4.52	3.70	3.71	3.34
Station 4	3.01	3.08	2.99	2.78	2.78	2.98	3.28	3.30	2.96	2.99	2.93	2.97
Evenness J'												
Station 1	0.76	0.87	0.86	0.86	0.86	0.90	0.92	0.91	0.86	0.85	0.86	0.87
Station 2	0.88	0.88	0.89	0.91	0.90	0.94	0.95	0.93	0.93	0.88	0.92	0.92
Station 3	0.94	0.93	0.91	0.91	0.91	0.89	0.92	0.91	0.92	0.94	0.95	0.95
Station 4	0.88	0.90	0.89	0.90	0.90	0.90	0.89	0.95	0.92	0.93	0.94	0.95

monthly sampling collections, September 2004, July 2004, August 2004, May 2004, April 2004 and December 2004. The only associated environmental variable, DO, was with the fourth CCA axis, and heavily impacted in the monsoon (November 2004 and October 2004) and summer (June 2004). Most of the copepod species were concentrated on the first CCA axis (Figure 5B). Rainfall was related to *Acartia southwelli*, air temperature was related to *Calocalanus pavo*, surface water temperature was related to *Acrocalanus monochus* and *Calanus tenuicornis*, while salinity was related to *A. gracilis*, DO was related to *Acartio danae* and *Oithona similis*, and pH was related to *Eucalanus elongatus* at Station 1. Nutrients (nitrate, nitrite, phosphate and silicate) were related to *E. elongatus*, *A. spinicauda*, *Temora stylifera*, *O. rigida*, *A. negligens*, *Microsetella norvegica*, *O. nana* and *A. southwelli* at Station 1.

At Station 2, the first CCA axis separated pH, DO, rainfall and nitrite along with four monthly sampling collections, June 2004, August 2004, July 2004 and May 2004 (Figure 6A). The second CCA axis separated silicate, nitrate and phosphate along with four monthly sampling collections, September 2004, November 2004, October 2004 and December 2004. The third CCA axis separated the temperature (air and surface water) and salinity along with three loosely related monthly sampling collections, January 2005, February 2005 and March 2005. The fourth CCA axis, in summer, was not strongly associated with any single variable, but with the April 2004 sample. Most of the copepod species were found spread equally on all axes (Figure 6B). Rainfall was related to *Tortanus forcipatus*, air temperature was related to *A. danae*, *Euterpina acutifrons* and *E. attenuatus*, while surface water temperature and salinity were related to *Pseudodiaptomus aurivilli*, *Euphausia brevis* and *Miracia efferata*. Dissolved oxygen was related to *O. similis*, pH was related to *C. tenuicornis*, *Corycaeus forcipatus* and *C. anglicus* at Station 2. Nutrients (nitrate, phosphate and silicate) were related to *Acrocalanus gracilis*, *Labidocera acuta* and *Metacalanus aurivilli* at Station 2.

At Station 3, only one environmental variable, rainfall, condensed on the first CCA axis, and it strongly associated six pre-monsoon and monsoon monthly sampling collections, April 2004, May 2004, August 2004, November 2004, September 2004 and October 2004 (Figure 7A). The second CCA axis separated nitrate, silicate, DO, phosphate and nitrite along with two monthly sampling collections, June 2004 and July 2004. On the third CCA axis, the only environmental factor was pH along with three monthly sampling collections, February 2005, January 2005 and December 2004. The fourth CCA axis separated the temperature (air and surface water) and salinity along with a post-monsoon month, March 2005. Most of the copepod species were found spread equally on all axes (Figure 7B). Rainfall was related to *Acartia spinicauda* and *L. acuta*, air temperature was related to *Clytemnestra dorsipinnatus*, *E. acutifrons* and *E. attenuatus*, surface water temperature was related to *P. annandalei, Centropages elongatus, C. danae* and *O. brevicornis*, salinity was related to *Nannocalanus minor*, DO was related to *Paracalanus parvus*, pH was related to *Euchaeta marina* at Station 3. Nutrients (nitrate and silicate) were related to *A. erythraea* and *L. acuta* at Station 3.

At Station 4, the first CCA axis separated the temperature (air and surface water) along with two monthly sampling collections, April 2004 and May 2004 (Figure 8A). The second CCA axis separated nitrite, silicate, rainfall, nitrate and phosphate along with six monthly sampling collections, November 2004, October 2004, September 2004, June 2004, July 2004 and August 2004. On the third CCA axis, the only environmental variable was DO along with two monthly sampling collections, December 2004 and February 2005. The fourth CCA axis separated pH and salinity along with two monthly sampling collections, January 2005 and March 2005. Most of the copepod species were found spread equally on all axes (Figure 8B). Rainfall was related to *E. marina*, temperature (air and surface water), salinity and DO were related to *Acrocalanus gibber*, pH was related to *C. danae* at Station 4. Nutrients (nitrate, nitrite, phosphate and silicate) were related to *N. minor*, *Acartia danae, Acrocalanus gibber, A. longicornis, E. marina* and *Copilia mirabilis* at Station 4.

The copepod population abundance (i.e. summed abundance of all species) showed a positive correlation with temperature and salinity and a negative correlation with rainfall, DO and pH. At Station 1, the correlation of copepod species diversity with population abundance was highly significant ($r = 0.76$), as was that of species richness with species diversity ($r = 0.87$). At Station 2, the correlation of species diversity with population abundance ($r = 0.80$) and species richness ($r = 0.79$) was significant at ($P < 0.01$). At Station 3, the

Table 5. CCA details and correlation of variables with the different axes.

Axes	1	2	3	4
Station 1				
Eigenvalues	0.085	0.052	0.028	0.019
Species–environment correlations	0.991	0.994	0.993	0.962
Cumulative percentage variance				
of species data	36.426	58.713	70.852	78.972
of species–environment	37.413	60.304	72.772	81.112
Correlation coefficient				
Rainfall	−0.311	−0.041	−0.255	0.048
Atmospheric temperature	0.603	−0.189	−0.601	0.066
Surface water temperature	0.39	0.038	−0.618	0.082
Salinity	−0.062	−0.438	−0.567	0.083
pH	0.119	0.077	−0.701	0.276
Dissolved oxygen	−0.048	0.273	0.665	0.051
Nitrite	0.485	0.231	0.617	0.168
Nitrate	0.285	0.554	0.381	0.288
Phosphate	−0.236	0	0.846	−0.06
Silicate	−0.075	0	0.68	0.086
Station 2				
Eigenvalues	0.064	0.048	0.031	0.02
Species–environment correlations	0.999	0.968	1	0.975
Cumulative percentage variance				
of species data	26.933	46.878	60.012	68.326
of species–environment	29.835	51.929	66.479	75.688
Correlation coefficient				
Rainfall	0.673	0.14	0.435	0.289
Atmospheric temperature	−0.575	−0.026	−0.473	−0.14
Surface water temperature	−0.564	−0.205	−0.274	−0.329
Salinity	−0.713	−0.221	−0.478	−0.156
pH	0.091	0.666	−0.17	−0.105
Dissolved oxygen	0.114	0.06	0.379	0.327
Nitrite	0.813	0.026	0.341	−0.048
Nitrate	0.314	−0.081	0.652	0.297
Phosphate	0.385	−0.118	0.39	0.223
Silicate	0.793	−0.022	0.455	−0.003
Station 3				
Eigenvalues	0.043	0.028	0.023	0.016
Species–environment correlations	0.993	1	0.999	0.997
Cumulative percentage variance				
of species data	31.595	52.402	69.468	81.618
of species–environment	32.437	53.798	71.319	83.793
Correlation coefficient				
Rainfall	0.675	0.31	0.239	−0.092
Atmospheric temperature	−0.423	0.323	−0.548	−0.341
Surface water temperature	−0.399	0.546	−0.499	−0.34
Salinity	−0.746	0.054	−0.207	0.014
pH	−0.113	−0.398	0.193	−0.381
Dissolved oxygen	0.622	−0.223	−0.128	−0.05
Nitrite	0.198	−0.468	0.395	−0.2
Nitrate	0.283	−0.07	0.257	−0.458
Phosphate	0.2	−0.434	0.361	−0.096
Silicate	0.438	−0.094	0.278	−0.117
Station 4				
Eigenvalues	0.056	0.026	0.022	0.007
Species–environment correlations	0.959	1	0.974	0.998
Cumulative percentage variance				
of species data	40.214	58.714	74.548	79.842
of species–environment	42.989	62.765	79.692	85.351
Correlation coefficient				
Rainfall	0.417	−0.465	0.62	0.123
Atmospheric temperature	0.001	0.677	0.097	0.226
Surface water temperature	0.07	0.65	0.121	0.307
Salinity	−0.71	0.478	−0.403	0.018
pH	−0.034	0.276	−0.231	−0.118
Dissolved oxygen	−0.046	−0.143	0.715	0.261
Nitrite	0.046	−0.513	0.534	−0.116
Nitrate	0.606	−0.233	0.502	0.084
Phosphate	0.734	−0.33	0.286	−0.067
Silicate	0.362	−0.407	0.66	0.017

Continued

Table 5. Continued.

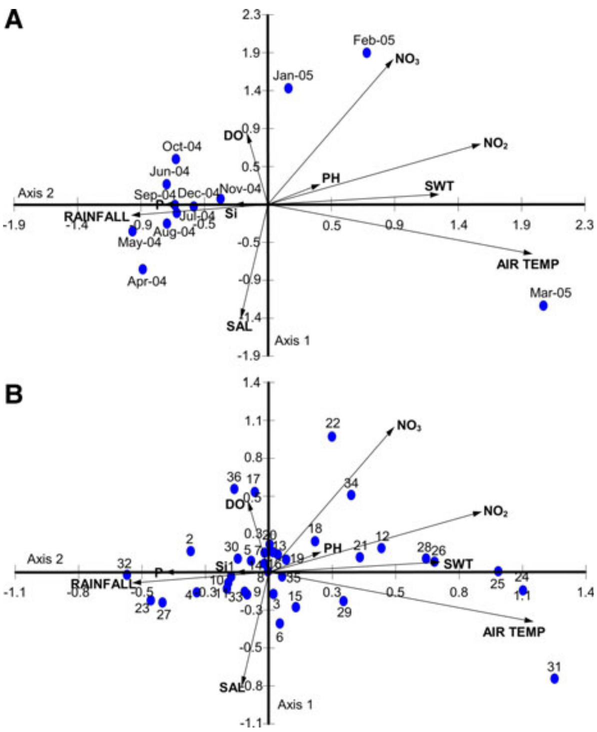

Fig. 5. (A) CCA showing scatter plot for 12 monthly sampling vs ten environmental variables at Station 1; (B) CCA showing scatter plot for copepod species vs environmental variables at Station 1 (species numbers refer to Table 3).

correlation of copepod species diversity with population abundance ($\underline{r} = 0.63$) was significant. Also, the correlation of species richness with species diversity was also highly significant ($r = 0.93$). At Station 4, the correlation of species diversity with population abundance ($r = 0.74$) and species richness ($r = 0.989$) was significant at $P < 0.01$.

DISCUSSION

Rainfall in south-eastern India is largely influenced by the north-east monsoon. In the mouth of the Coleroon, the variations in physico-chemical parameters are closely associated with the strong variation in copepod abundance and distribution. Rainfall shows a marked annual cycle and, correspondingly, so do the hydrological variables in the estuarine system. During the monsoon rainfall, the Coleroon estuary receives heavy freshwater inflow from land drainage, associated with which were the abrupt changes we found in all the analysed physico-chemical variables. Peak values of rainfall in the present study occurred during the monsoon month of

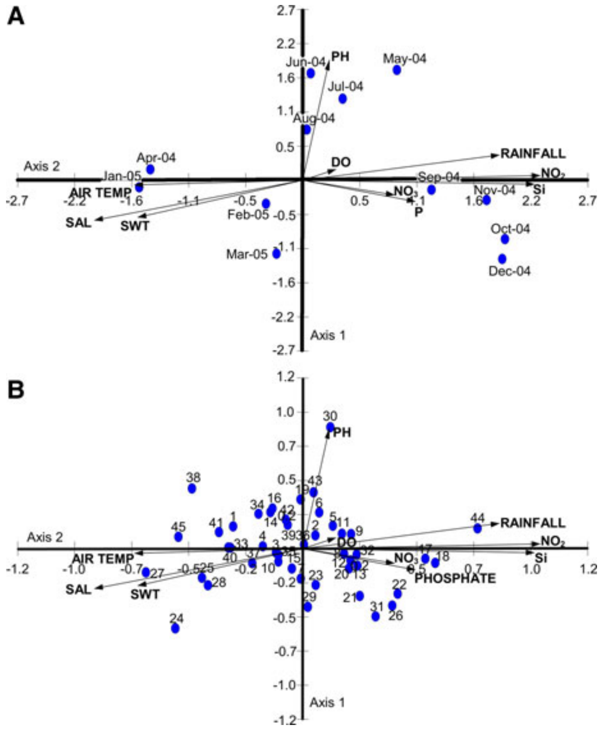

Fig. 6. (A) CCA showing scatter plot for 12 monthly sampling vs ten environmental variables at Station 2; (B) CCA showing scatter plot for copepod species vs environmental variables at Station 2 (species numbers refer to Table 3).

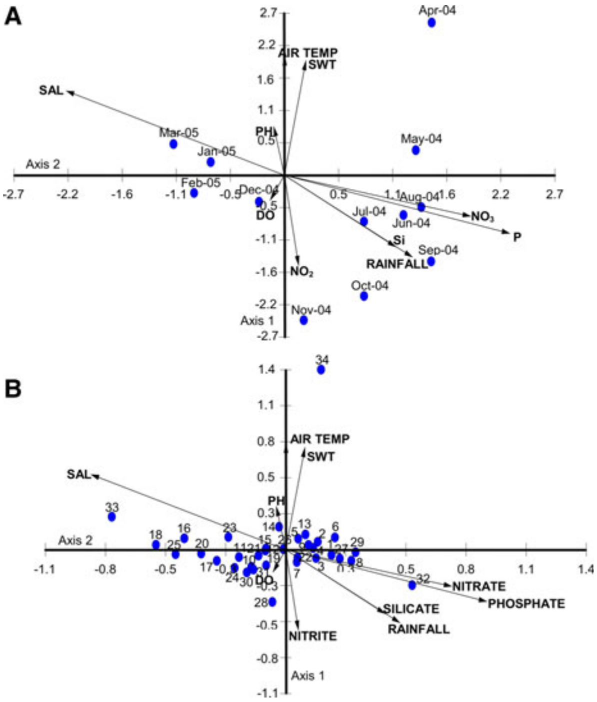

Fig. 8. (A) CCA showing scatter plot for 12 monthly sampling vs ten environmental variables at Station 4; (B) CCA showing scatter plot for copepod species vs environmental variables at Station 4 (species numbers refer to Table 3).

October (Rajkumar *et al.*, 2009). Tidal rhythm, water currents and evaporation in summer produced only slight variation in those variables.

The surface water temperature showed an increasing trend from December to April, associated with high solar radiation, and low temperature recorded during the monsoon could be due to strong sea breezes, rainfall and cloudy skies (Ashok Prabu *et al.*, 2008). The spatial variation in temperature could be due to the intensity of prevailing currents and consequent lateral mixing (Rajkumar *et al.*, 2009). This can be further explained by the correlation between air and surface water temperature. The strong positive correlations observed between air and surface water temperature at all four stations ranged between 0.923 and 0.982.

In estuaries, salinity is generally the main hydrological determinant of copepod diversity and distribution (Mouny & Dauvin, 2002; Tackx *et al.*, 2004; Marques *et al.*, 2006). Generally, salinity changes in estuaries, backwaters and mangroves are due to two predominant factors: firstly, the influx of freshwater from land run-off largely caused by monsoons; secondly, tidal variations. This is illustrated by the negative correlation ($r = -0.23$ at Station 1, $r = -0.97$ at Station 2, $r = -0.89$ at Station 3 and $r = -0.88$ at Station 4) obtained between salinity and rainfall. In the study area, salinity showed a significant positive correlation with temperature. The higher salinity found during post-monsoon and summer was most probably caused by the high evaporation (Rajkumar *et al.*, 2009).

Surface waters remained of high pH throughout the study period at all stations, with maximum values during the pre monsoon, post monsoon and summer, and minimum during the monsoon. Generally, fluctuations in pH throughout the year are attributed to factors such as the removal of

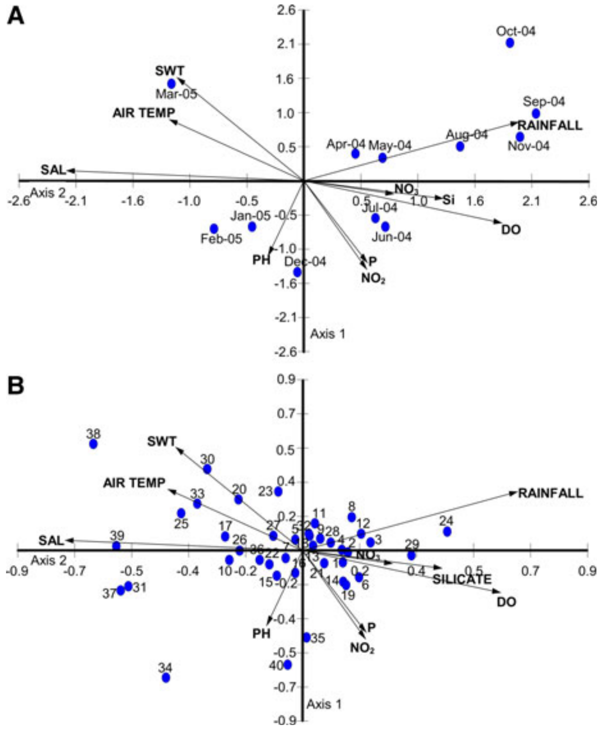

Fig. 7. (A) CCA showing scatter plot for 12 monthly sampling vs ten environmental variables at Station 3; (B) CCA showing scatter plot for copepod species vs environmental variables at Station 3 (species numbers refer to Table 3).

CO_2 by photosynthesis through bicarbonate degradation, dilution of seawater by freshwater influx, reduction of temperature and decomposition of organic matter (Ashok Prabu *et al.*, 2008). The observed higher pH in summer might be caused by seawater inundation and relatively high biological activity (Rajkumar *et al.*, 2009), manifest in the abundance of photosynthetic organisms (Saravanakumar *et al.*, 2008).

Temperature and salinity both affect the dissolution of oxygen (Rajkumar *et al.*, 2009). The presently recorded lower summer values could be mainly due to reduced agitation and turbulence of the coastal and estuarine waters. The recorded higher DO concentration during the monsoon season might be due to the cumulative effect of higher wind velocity coupled with heavy rainfall and the resultant mixing (Ashok Prabu *et al.*, 2008). Rajkumar *et al.* (2009) have attributed the seasonal variation in DO mainly to freshwater influx and terrigenous impact of sediments. Further, the presently obtained significant positive relationship between rainfall and nutrients, particularly at Stations 2–4 (Figure 2), suggests that river leaching and scouring constituted the main source of the nutrients in the estuary.

In the marine environment, nutrients are required for growth, reproduction and the metabolic activities of primary producers (Ashok Prabu *et al.*, 2008). Distributions of nutrients are based mainly on the season, tidal conditions and freshwater flow from land sources. The high concentration of inorganic phosphate observed during the monsoon season might be due to the washing down of land drainage (Saravanakumar *et al.*, 2008). Further, regeneration and release of total phosphorus from bottom mud into the water column by turbulence and mixing could also contribute to the recorded higher monsoonal values (Ashok Prabu *et al.*, 2008). The recorded highest phosphate and nitrate concentrations during the monsoon season could be attributed to the heavy rainfall, land run-off, nutrient-enriched shrimp farm discharge and autochthonous sources. In addition, anthropogenic activities like fertilizer application on agricultural fields and alkyl phosphates used in households as detergents could be other sources for the higher amounts of inorganic nitrate and phosphate (Ashok Prabu *et al.*, 2008; Rajkumar *et al.*, 2009). The observed maximum values of nitrate during the monsoon season at all the stations may be due to anthropogenic inputs and organic matter from the catchment area during the ebb tide (Ashok Prabu *et al.*, 2008). The low values recorded during non-monsoonal periods may be due to decreased run-off and to the utilization of phosphates by phytoplankton, as evidenced by high photosynthetic activity and, at Station 1, also due to the dominance of marine water having negligible amounts of nitrate (Rajkumar *et al.*, 2009).

The silicate content was high relative to that of the other nutrients (nitrate, nitrite and phosphate) and the recorded higher monsoonal values may be due to the heavy influx of freshwater derived from land drainage carrying silicate leached out from rocks and from the bottom sediment (Ashok Prabu *et al.*, 2008). The low concentration of silicate recorded during the post-monsoon and summer seasons could be attributed to the incorporation of silicate by phytoplankton (Ashok Prabu *et al.*, 2008).

During the present study, the planktonic copepods of the estuary were represented by 104 species belonging to 38 genera of 26 families. Calanoid copepods constituted the dominant group represented by 65 species. Cyclopoids and Harpacticoids were represented by 28 and 11 species, respectively. Thus, the species composition of copepods in Coleroon estuary is comparable with those of the Bahuda estuary (Mishra & Panigrahy, 1996), the Hooghly estuary (Sarkar *et al.*, 1986), the Godavari estuary (Padmavathi & Satyanarayana, 1996), the Mandovi and Zuari estuaries (Dalal & Goswami, 2001) and the Vellar estuary (Kumar, 1991), but was different from that of the Mandarmani Creek (Mitra *et al.*, 1990). In the Mandarmani Creek, out of the 31 species of planktonic copepods, Harpacticoida was represented by only one species (*Macrosetella glacialis*), as against 11 species encountered during the present study. In general, the highest numbers of species were found during the summer season followed by the post-monsoon season. The relative peak in copepods during the summer season may be attributed to the recruitment of neritic species through massive ingress of seawater into the estuary due to tidal influence. A similar pattern of species abundance of copepods has also been reported from many other Indian estuaries (Mishra & Panigrahy, 1996; Ramaiah & Nair, 1997; Dalal & Goswami, 2001).

Salinity is the main hydrological parameter controlling plankton diversity in temperate estuaries (Mouny & Dauvin, 2002; Tackx *et al.*, 2004; Marques *et al.*, 2006). This is reflected in the present study, where at all stations (Figures 5–8) salinity was also negatively related to rainfall and nutrients (Si, NO3, NO_2 and P). Correlation between salinity and copepod abundance was lowest at Station 1, increasing upstream ($r = 0.29$ at Station 1; $r = 0.66$ at Station 2; $r = 0.79$ at Station 3 and $r = 0.86$ at Station 4). Furthermore, as in all estuaries, salinity preference is a primary way to group the species (Wooldridge, 1999), which can be divided into three main categories (Dalal & Goswami, 2001).

Category I. Perennial copepod (Euryhaline) species, which are found during most of the year. The species belonging to this group include: *A. longicornis*, *A. monochus*, *A. gracilis*, *A. gibber*, *E. elongatus*, *E. crassus*, *E. subcrassus*, *P. parvus*, *P. annandalei*, *L. acuta*, *L. pavo*, *L. pectinata*, *Pontella spinipes*, *A. clausi*, *A. spinicauda*, *A. danae*, *T. discaudata*, *T. forcipatus*, *O. similis*, *O. brevicornis*, *M. gracilis*, *M. norvegica*, *M. rosea* and *E. acutifrons*. These species contribute over 60% of the total copepod population at any given time. They can be considered as the resident species of the estuary.

Category II. Seasonal copepods (Stenohaline) occurred mainly in marine brackish water (15–30 psu) and had a limited period of existence in the estuary. They are *P. aculeatus*, *P. aurivilli*, *C. danae*, *C. furcatus*, *A. erythraea*, *O. rigida*, *O. linearis*, *N. minor*, *Scolecithrix danae* and *Candacia bradyi*. These species were abundant during the post monsoon period when the salinity was progressively increasing.

Category III. Casual migrants that were found sporadically in plankton catches. They constitute: (a) both the marine or stenohaline (>30 psu) forms and include *T. turbinata*, *C. mirabilis*, *Clytemnestra scutellata*, *T. gracilis*, *C. catus* and *Longipedia weberi*; (b) oligostenohaline or brackish freshwater (>5–15 psu) forms like *Pontellopsis herdmani*, *Oncaea venusta*, *O. conifera*, *L. minuta*, *Metis jousseaumei*, *Sapphirina ovatolaneaolata*, *S. nigromaculata*; and (c) limnetic (<5 psu) forms particularly *Mesocyclops hyalinus*. The period of existence and numerical abundance of each of these showed marked seasonal fluctuations.

Temperature is also very important in determining the seasonality in copepods species composition (David *et al.*, 2005;

Lionard *et al.*, 2005; Rahman, 2006). During the present observation, species belonging to the families, Paracalanidae, Acartiidae, Tachidiidae, Ectinosomidae and Oithonidae dominated the copepod counts, occurring throughout the year. Seasonal variations in copepod abundance similar to those observed in the present study have been reported from the Caribbean and adjacent areas (Rios-Jara, 1998). In contrast, studies from the Caribbean coastal coral reef environment found no evidence of seasonality (Moore & Sander, 1976). The species, *A. erythraea, A. spinicauda, A. danae, P. parvus, O. brevicornis, O. similis* and *E. acutifrons* were dominant, and in the present study they successfully flourished year-round. The abundance of these species might be due to their ability to breed continuously (Godhantaraman, 1994). Dwivedi *et al.* (1974) also reported similar dominance of these species in bulk to the biomass of macrozooplankton in the Mandovi and Zuari estuaries. Among the copepods observed, *A. erythraea* and *O. brevicornis* were predominant throughout the year. This may be due to their continuous breeding behaviour, quick larval development and the fact that they adapt well to the environmental conditions of the estuaries. Chandramohan (1977) reported this type of dominance of *Acartia* spp. among calanoids in the Godavari estuary and by Madhupratap (1999) in the Cochin backwaters. Most of them are neritic and abundant in coastal waters (Yoo *et al.*, 1991), and the cyclopoids *Oithona* spp. were recorded in the Vellar estuary (Kumar, 1991). *Acartia* and *Oithona* species are frequently dominant in estuaries and coastal areas, for example in the inlet waters of the Sandy Hook Bay area of New Jersey (Sage & Herman, 1972), Maizuru Bay, Japan (Ueda, 1987) and Malaysian waters (Chong & Chua, 1975). These genera occur frequently in Bombay Harbour–Thana creek–Bassein creek during high salinity periods (Ramaiah & Nair, 1997). In the present study, the order of abundance of the copepod groups was Calanoida > Cyclopoida > Harpacticoida, although they show considerable spatial and temporal variations. In the present study, the copepod population abundance showed a gradual decreasing trend during monsoon season (October–December). Similar reports of monsoonal minima in copepod densities have been observed in Indian estuaries previously (Madhupradap & Rao, 1979; Goswami, 1982; Sarkar *et al.*, 1986; Madhupradap, 1999). The highest densities were found to occur in the summer and post-monsoon seasons due to increased salinity, and to be associated with peaks in phytoplankton abundance (McKinnon & Throlld, 1993; Mishra & Panigrahy, 1996). The population densities were higher in the estuary than the adjacent sea because the estuary receives more organic enrichment from the catchment areas.

Among the *Acartia* genus, *A. erythraea, A. danae* and *A. southwelli* were dominant, while in the *Oithona* genus, *O. brevicornis* and *O. similis* were predominant throughout the study period. Among all zooplankton, copepods formed the most important group in the zooplankton community throughout the year, constituting 67.9–97% of the total zooplankton biomass. Among the copepods, the suborder, Calanoida comprised a major component with more species. A gradual decrease was discernible from October to December, and these peaks can be attributed to the favourable hydrological conditions. The bulk of the copepod population was contributed by five genera viz. *Paracalanus, Acrocalanus, Acartia, Euterpina* and *Oithona*. The common species were *P. parvus, A. gracilis, A. gibber, A. erythraea, A. spinicauda, A. danae, E. acutifrons, O. brevicornis* and *O. rigida*. An almost similar result was observed by Kumar (1991). The calanoid genus, *Acartia* comprises over 70 species and is distributed throughout the world's oceans (Mauchline, 1998). Most of them are neritic and abundant in coastal waters (Yoo *et al.*, 1991). Copepods of *A. erythraea* in subtropical waters generally live on, or slightly above, the bottom in near-shore waters during the day and maintain their position against weak water currents (Ueda *et al.*, 1983). They are highly concentrated in the surface layer in the afternoon (Checkley *et al.*, 1992). Both *A. erythraea* and *P. parvus* are common in the productive coastal water of southern China (Chen, 1992) and south of Java (Tranter, 1977).

In the present study, the minimum species diversity occurred during the monsoon season. This might be due to washing out of allochthonous and even some autochthonous species by the heavy monsoonal flood (Rajkumar *et al.*, 2009). The turbidity might be another reason for the lower diversity (Goswami, 1982).

The maximum diversity was recorded during post monsoon seasons when salinity of the water is high. Rao (1977) reported similar findings in Indian estuaries, Goswami (1982) from Mandovi–Zuari estuaries, Haridass *et al.* (1980) from the Indian Ocean and Madhupradap *et al.* (1981) from the Andaman Sea. The copepod diversity due to high salinity can also be explained by the species diversity and salinity in Station 3, where salinity and copepod diversity were higher than the salinity and copepod diversity of other stations. In the present study, the species diversity showed a significant relationship with species richness ($P < 0.01$ at Station1; $P < 0.01$ at Station 2; $P < 0.01$ at Station. 3 and $P < 0.01$ at Station 4). In the present study a reverse trend was observed in evenness values. The observed very low species evenness was obtained in April due to the unequal distribution of the species in these months, and high evenness values were obtained during the monsoon and post monsoon seasons at all the stations, which indicated that the species were relatively equally distributed and thus not allowing a single species to dominate over others. Kumar (1991) made similar observations from Parangipettai coastal waters.

CONCLUSION

Monthly sampling of physico-chemical variables and copepods at four stations in the Coleroon estuary showed at least 104 species to be present, reflecting its high biodiversity and high fertility. The study demonstrated a clear annual cycle in species composition, driven largely by rainfall and associated salinity and nutrient variations. The disastrous tsunami of 26 December 2004 occurred between our December and January sampling trips. However, any effect the tsunami may have had on copepod species abundance or nutrient levels is masked by the annual variation (except perhaps for nitrite).

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