Distribution of heavy metals in the vicinity of a nuclear power plant, east coast of India: with emphasis on copper concentration and primary productivity

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Seawater samples collected in the vicinity of MAPS (Madras Atomic Power Station) from 17 stations covering an area of 4 km² were analysed for distribution of heavy metals viz. iron, copper, cadmium and mercury. Mercury was analysed by cold vapor Atomic Absorption Spectrometry (AAS) and the other heavy metals by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). Water samples were found to have heavy metals such as Fe (26-85 µg l⁻¹), Cu (0.05-5.1 µg l⁻¹); Cd (0.5-1.7 µg l⁻¹) and Hg (0.03-1.5 µg l⁻¹). Samples from the power plant cooling system and condenser outfall were specifically analysed for copper and primary production. Copper concentrations were in the range 1 – 2.2 µg l⁻¹. Primary productivity was low on passing through the power plant cooling circuit. However, it was found to recover once the effluent mixed with the ambient sea. Present study infers that heavy metal concentrations in the vicinity of the power station outfall are comparable to unpolluted pelagic waters of the Bay.

[Keywords: Power plant, Heavy metals, Cruise, Bay of Bengal, Copper, Primary productivity]

Introduction

Marine pollution has long been a problem in the world’s coastal zones and there is ever increasing pressure on marine ecosystems¹². Heavy metals are one of the constituents that affect marine ecosystem. Potential toxicity of heavy metals in aquatic ecosystem is determined by their chemical form. Changes in oxidation state of the heavy metal can have profound effect on their toxicity and bioavailability³. Excessive concentration of heavy metals in the marine environment can affect marine biota and pose risk to human consumers of sea food⁴⁵. Degree of heavy metals in seawater and their distribution play an important role in influencing the productivity of marine ecosystem⁴⁶⁷. Copper and its alloys are extensively used as heat exchanger materials in power plants and other industries⁸.

Present study was carried out in the vicinity of a nuclear power plant located on the East Coast of India, drawing cooling water from coastal waters of Bay of Bengal. Studies of trace metal in coastal waters of Bay of Bengal⁹ are scarce. It receives significant inputs of freshwater during monsoon season, which influences the salinity even up to Andaman Islands in the south. Surface water currents and wind patterns also read out the bay processes¹⁰¹¹. Present study probes the extent of heavy metals pollution, if any, released from the power plant, with emphasis on copper and its effect on the primary productivity. It also presents primary productivity in the coastal waters as well as at the power plant intake point and condenser outfall, to ascertain the influence of the power plant. The same is compared with historic data generated 25 years ago when the power plant was not in operation. In addition, the levels of trace metals reported in other open ocean and coastal environments of Indian seas are also reviewed and discussed.

Materials and Methods

Description of study area

The study was carried out in the vicinity of Madras Atomic Power Station (MAPS), located at Kalpakkam, East coast of India. Kalpakkam (12°33'N and 80°11'E), located about 70 km south of Chennai (Fig. 1a). The power station uses a subsea-bed tunnel for drawing cooling water from the sea. The seawater intake is located 1 m below the lowest low water of springs. The shoreline at Kalpakkam is open to the Bay of Bengal and the tidal range is 0.3 to 1.5 m. The MAPS units were commissioned in 1983 and intermittent chlorination was used to control
biofouling till 1987. After a major biofouling problem (in 1987), low dose continuous chlorination (using chlorine gas) mode was put in practice with a total residual oxidant level of 0.1 to 0.4 ppm at outfall. The outfall receives the discharge from both the condenser and process seawater cooling systems\textsuperscript{12}. The discharged water forms a canal on the shore and mixes with the coastal waters. The distance of mixing point varies with the seasons and depends on the prevailing monsoon and the current pattern in the coastal waters\textsuperscript{13}.

Sample Collection

Water samples were collected using the coastal research vessel \textit{Sagar Purvi} (Fig. 1b). Subsurface water samples were collected from 17 stations covering an area of 4 km\textsuperscript{2} and are illustrated in Fig. 1c. Station positions were fixed using an onboard differential GPS. High density poly propylene bottles

Fig. 1a—Map showing the study site of Kalpakkam, East Coast of India

Fig. 1b—Aerial image of the study area

Fig. 1c—Details of sampling stations during the Sagar Purvi cruise
were used for collecting and storing seawater for heavy metal analyses. Before sampling, they were cleaned by soaking in 7M nitric acid for 5 days. Sampling of seawater for heavy metal analysis was carried out using a non-metallic Niskin sampler as per standard procedures. The samples were kept at 4°C until the time of heavy metal analysis. The primary productivity of phytoplankton was determined by light and dark bottle method. 

**Heavy Metal Analysis**

The heavy metal analysis was carried out at the National Center for Compositional Characterisation of Materials (CCCM), Hyderabad, India. The metals Fe, Cu and Cd, were analysed using inductively coupled plasma optical emission spectrophotometer ICP-OES (Model: Jobin Yvon, JY-2000, France). The determination of Fe was carried out using ICP-OES directly by standard addition method. Samples for Cu, Cd and Hg, were pre-concentrated by a factor of ten by sodium diethyl dithiocarbamate and chloroform extraction method. All the extraction and heating processes were conducted in a class-100 clean fume hood. Mercury was analysed by cold vapour Atomic Absorption Spectrophotometer AAS (ECIL, India) by standard addition method. Table 1 describes the standard addition studies and recovery of trace elements. As can be seen, the recovery of metals was found to be ~ 90% and the limits of detection for the various heavy metals were: Fe: 10.5 µg/l; Cu: 0.05 µg/l; Cd: 0.3 µg/l and Hg: 0.03 µg/l.

**Statistical Method**

The aim of the statistical analysis carried out for copper concentrations in this study is to see if the test statistic is ‘unlikely’ (by ‘unlikely’ we mean that the probability P of getting such an extreme result is less than the level of significance, α). The two-tailed test using α = 5% level of significance is equivalent to calculating a 95% confidence interval for the mean and observe if this contains the sample mean. The statistical test was used specifically for copper concentrations from the present study and three earlier studies from east coast of India were compared with the data of C-MARS, which is a reference laboratory.

**Results**

Table 2 is the schematic illustration of the meteorological details of the Kalpakkam coast. Data on the air temperature, wind speed, rainfall along with sea current and sea surface temperature (SST) are also described. Most of the rainfall occurs during the NE monsoon unlike the other parts of the peninsular India which receives bulk of rainfall during SW monsoon. The maximum rainfall recorded during a year ranged from 270 - 310 mm. Air temperature reaches a maximum (as high as 43°C) during summer months and a minimum value ~20°C during winter. Annual SST ranges between 26.5 – 31.5°C.

Table 3 illustrates total dissolvable copper recorded from various studies particularly on east coast. Column I and II of Table 3 detail the copper

**Table 1—Standard addition studies and recovery of trace elements**

<table>
<thead>
<tr>
<th>Element</th>
<th>Standard added (µg l⁻¹)</th>
<th>Limit of Detection (µg l⁻¹)</th>
<th>Mean Recovery</th>
<th>% Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (Fe)</td>
<td>1</td>
<td>10.5</td>
<td>1.04 ± 0.06</td>
<td>100</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>1</td>
<td>0.05</td>
<td>0.92 ±0.05</td>
<td>90</td>
</tr>
<tr>
<td>Cadmium(Cd)</td>
<td>1</td>
<td>0.30</td>
<td>0.91 ±0.50</td>
<td>90</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>1</td>
<td>0.03</td>
<td>0.89 ±0.04</td>
<td>90</td>
</tr>
</tbody>
</table>

**Table 2—Typical annual meteorological features of Kalpakkam coast**

<table>
<thead>
<tr>
<th>Months</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
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<tbody>
<tr>
<td>Wind Speed</td>
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<td></td>
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<tr>
<td></td>
<td>NE Monsoon</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>SW Monsoon</td>
<td></td>
</tr>
<tr>
<td>Sea Current</td>
<td>Southerly Current</td>
<td>0.1 – 1.3 km hr⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Northerly Current</td>
<td>0.2 – 1.8 km hr⁻¹</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Most of the rainfall is during North East monsoon, the average maximum rainfall varies from 200 - 300 mm</td>
<td></td>
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</tr>
<tr>
<td>Air Temperature</td>
<td>The maximum air temperature ~43°C and minimum ~ 20°C</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>SST</td>
<td>Ranges from 26.5–31.5°C</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

SST = sea surface temperature
Table 3—Total dissolved copper recorded from various studies, East coast of India

<table>
<thead>
<tr>
<th>S. No</th>
<th>I(^1)</th>
<th>II(^2)</th>
<th>III(^3)</th>
<th>IV(^4)</th>
<th>V(^5)</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>239</td>
<td>127</td>
<td>22</td>
<td>49</td>
<td>2.11 ±0.4</td>
<td>1.39 ±0.15</td>
</tr>
<tr>
<td>2</td>
<td>255</td>
<td>176</td>
<td>33</td>
<td>52</td>
<td>2.18 ±0.4</td>
<td>2.12 ±0.23</td>
</tr>
<tr>
<td>3</td>
<td>273</td>
<td>240</td>
<td>19</td>
<td>43</td>
<td>2.12 ±0.4</td>
<td>2.24 ±0.12</td>
</tr>
<tr>
<td>4</td>
<td>158</td>
<td>195</td>
<td>23</td>
<td>35</td>
<td>2.10 ±0.3</td>
<td>3.90 ±0.34</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>252</td>
<td>25</td>
<td>34</td>
<td>2.20 ±0.5</td>
<td>2.10 ±0.40</td>
</tr>
<tr>
<td>6</td>
<td>164</td>
<td>197</td>
<td>22</td>
<td>49</td>
<td>2.11 ±0.4</td>
<td>2.40 ±0.43</td>
</tr>
<tr>
<td>7</td>
<td>162</td>
<td>123</td>
<td>43</td>
<td>46</td>
<td>2.15 ±0.4</td>
<td>4.50 ±0.97</td>
</tr>
<tr>
<td>8</td>
<td>143</td>
<td>135</td>
<td>35</td>
<td>50</td>
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</tr>
<tr>
<td>9</td>
<td>202</td>
<td>106</td>
<td>24</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>236</td>
<td>85</td>
<td>20</td>
<td>--</td>
<td>--</td>
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</tr>
</tbody>
</table>

Selvaraj\(^6\) (1999); Rao \(^6\) \textit{et al.}, 2001; Satpathy \textit{et al.}, 2006; Iyer\(^9\). VI = present data from MAPS cooling circuit samples. The typical data on copper presented in this table by different authors need not correspond to the same location.

Table 4 provides a comparison of heavy metal distribution in Indian seawaters. On the whole, East coast of India has relatively higher heavy metal concentrations when compared to the Arabian Sea on the West coast of India., Column I and II represent the polluted sites in the east coast, which are harbours with lot of maritime activity. Data in columns III and IV are from non-polluted sites on the east coast, wherein the copper values were low (0.7 to 5.0 µg l\(^-1\)). Table 5 describes the Gross Primary Productivity (GPP) values in the vicinity of MAPS recorded over two decades. The GPP values of seawater samples collected from the power plant intake area ranged from 22 – 34 mg C m\(^{-3}\) h\(^{-1}\). However, at the outfall there is significant reduction (up to 40 – 50 %) in GPP. Stations located more offshore had GPP values in the range of 22 – 32 mg C m\(^{-3}\) h\(^{-1}\). The nearby backwater systems, Sadras and Edayur, showed relatively high GPP values (60 mg C m\(^{-3}\) h\(^{-1}\)).

Fig. 2—Primary production data from the coastal waters of Kalpakkam. Re-plotted from Poornima \textit{et al.}, (2006) and Nair \textit{et al.}, (1987), GPP = Gross Primary Productivity.

Table 4—Comparison of heavy metal (µg l\(^{-1}\)) distribution data in Indian waters

| S No | Visakaptnam | Chennai\(^6\) | Bay of Bengal\(^6\) | Kalpakkam\(^*\) | C-MARS\(^9\) | Arabian Sea\(^{16,30}\) |
|------|-------------|--------------|------------------|-----------------|-----------|------------------|---|
| Copper | 18.4 – 70 | 35 | 16– 170 | 1.2 – 17.5 | 2.0 – 2.2 | 0.7 – 5.0 | 2.5 - 22 |
| Cadmium | 2.9 – 13 | 6.6 | 1.3 – 18 | 0.3 – 2.9 | 0.06 – 0.1 | 0.3 – 1.7 | 0.2 – 0.4 |
| Mercury | ND | ND | ND | 0.4 – 1.5 | 0.1 – 1.5 | 1-3 |
| Iron | ND | ND | 26 - 85 | 31 - 85 | 100 |
| Lead | 25 – 106 | 47 | 5 - 17 | 0.5 - 16 | ND | ND | 4 - 12 |

ND = No Data; * present study; † present study; Satyanarayana \textit{et al.}, 2001; Iyer\(^9\); Sadasivan and Tripathi\(^{30}\).

Table 5—Gross Primary Productivity (GPP) values in the vicinity of MAPS, Kalpakkam

<table>
<thead>
<tr>
<th>Stations</th>
<th>1987(^{41})</th>
<th>1987(^{41})</th>
<th>1987(^{41})</th>
<th>1987(^{41})</th>
<th>2002(^{36})</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake</td>
<td>22.0</td>
<td>26.0</td>
<td>34.5</td>
<td>27 ±6.3</td>
<td>27.6 ±6.6</td>
<td>22.8 ±1.2</td>
<td>28.0 ±2.2</td>
</tr>
<tr>
<td>Outfall</td>
<td>9.88</td>
<td>8.98</td>
<td>14.8</td>
<td>11 ±3.1</td>
<td>11.3 ±3.2</td>
<td>11.2 ±0.6</td>
<td>19.2 ±1.6</td>
</tr>
<tr>
<td>Coastal</td>
<td>27.3</td>
<td>22.2</td>
<td>24.0</td>
<td>24 ±2.5</td>
<td>25.6 ±4.2</td>
<td>26.5±2.2</td>
<td>32.8 ±2.2</td>
</tr>
</tbody>
</table>

GPP = mg C m\(^{-3}\) h\(^{-1}\); Nair (1987)\(^{41}\) data from different seasons; Poornima \textit{et al.}, 2006 = Laboratory Data.
primary productivity values of Kalpakkam coast recorded over a year and compared with primary productivity values recorded before the power plant went into operation (1981). There was no significant variation in the productivity values over the decades. Figure 3 illustrates the distribution of heavy metals in the water samples collected from the 17 stations (see Fig 1c) during the Sagar Purvi Cruise. The concentration of Fe ranged from 26 to 85 µg/l, Cu from <0.05 to 5.1 µg l⁻¹, Cd from <0.5 to 1.7 µg l⁻¹ and Hg values varied from 0.03 to 1.5 µg l⁻¹. Variations in the heavy metal concentration with respect to stations are not significant (P = > 0.2). The values of the heavy metal concentration are in the order of Fe<Cu<Cd<Hg.

A comparison of statistical test and their inference were prepared for the copper values and reported in Table 3. Table 6 and 7 describe the statistical significance of the copper values reported by earlier studies in comparison to the data from C-MARS, reported by Iyer et al.⁹. The mean of the copper concentration as reported by Iyer et al. is 2.14, therefore the SD is 0.04 and the standard error (SE) of the mean = \( \frac{0.04}{\sqrt{7}} = 0.015 \)

A 95% confidence interval (CI) test gave an idea of the true mean of copper concentration in coastal waters of Bay of Bengal. This is obtained as \( \text{Mean} \pm t \times \text{SE} \), where \( t \) is the appropriate two-tailed probability value of \((n-1)\text{df}\). Based on the observations, it can be 95% sure that the true mean of Cu concentration in coastal waters of Bay of Bengal is contained with the interval;

\[ 2.14 \pm 2.45 \times 0.015 \]
\[ \text{i.e. } (2.103 \text{ to } 2.177) \]

It is obvious that the average copper concentration reported in Table 3 was lower from that observed by Iyer, et al. (1999). Presuming that the distribution of the copper concentration from various studies reported in Table 3 is a true representative of the copper data, the test statistic was calculated assuming the Null Hypothesis is true with level of significance for the test, \( \alpha = 0.05 \) or 5%.

**Discussion**

Generally, surface waters concentrate trace levels of metals thereby making them useful indicators for
monitoring purposes as well as for detecting the source of pollution in the aquatic system. Speciation of metals in marine environment is a major factor in determining the bioavailability of the toxic heavy metals. Procedurally, metal speciation can be carried out with filtered (0.45 µm) and unfiltered seawater samples. Munksgaard and Parry assayed various metals ions from filtered and unfiltered seawater samples. They reported that in case of unfiltered seawater sample analysis, the widely used procedure of acidification (pH < 2.0) of seawater is likely to breakdown all the inorganic and organic metal complexes present in the sample. Generally at low pH, hydrogen ions (H\(^+\)) compete with metal ions for ligands in water, which are predominantly protonated. Therefore, the acid extraction procedure extracts the metals both in dissolved phase as well as from particulate bound metal ions. In the present investigation, unfiltered seawater samples were assayed for the heavy metal concentration off Kalpakkam coast, East coast of India. Metal concentrations in unfiltered seawater samples can be appreciably higher than dissolved metal concentration. Therefore, trace metals adsorbed and/or complexed to suspended matter are also important as they are mobile. Hence, a positive correlation should exist between suspended matter and total metal concentration in unfiltered seawater as exemplified. Generally, tidal flow and wave action can significantly increase the level of particulate matter and may play a role in chemical cycling of metals in coastal waters.

Copper occurs at very low levels in the oceanic environment, the availability of copper to an organism is controlled more by the chemical species of copper rather than the total copper concentration. Significant copper accumulation is unlikely to occur in open coastal areas, but can accumulate in the sediments of low flowing waters including streams, rivers and bays. Introduction of anthropogenic copper into aquatic environments from industry and agricultural sources is often detectable from metal concentrations in water, sediments and organisms. Excess metal can affect species composition and metabolic functions of microbial flora as well as other organisms if the metal is in a biologically available form. Determining biological availability in areas of high metal concentrations often includes measurement.
of cupric ion activity, which is biologically more potential. The distribution and speciation of copper is important and is affected by hydrographic conditions. Risø et al.,22 reported significant differences in copper concentration between well-mixed and stratified zones in coastal waters. They also observed that copper concentration varied much less in a well-mixed zone than across a stratified water column. In an assessment of particulate associated trace metals in the western Bay of Bengal, Satyanarayana et al.,23 observed that particulate copper profiles showed a continuous decrease from the surface to the bottom. They also found a correlation between copper and particulate organic carbon, suggesting biological uptake near the surface and transport to the sediments. In this study, seawater samples collected from different locations of the cooling circuit have shown that the copper levels are in the range 1.5 – 4.5 µg l⁻¹. The copper levels are more or less close to the values observed in the pelagic Bay of Bengal.9 Normally, high copper values are a result of natural processes occurring in the estuary mouth regions when there are no other known anthropogenic inputs of these heavy metals or mining5,7. The statistical results presented in Table 7 indicate that the copper values reported in the present study are in agreement with those recorded by Iyer.9 The values reported in the present study corroborate with the metal concentrations reported by C-MARS.9

According to Hoarse et al.,24 relatively unpolluted coastal seawaters have copper levels within the range 2 to 5 µg l⁻¹, while copper concentrations > 30 µg l⁻¹ are categorized as contamination. They also reported that although copper is an essential element for Mytilus edulis, a copper concentration of 15 µg l⁻¹ resulted in 50% mortality of adult M. edulis when exposed to 30 days. Reish, et al.,25 in their comprehensive review on pollution of marine organisms cited that copper can accumulate in the range 3.2 – 21 µg g⁻¹ dry weight in green algae and 3.5 – 7.5 µg g⁻¹ in brown algae. These copper concentrations have not affected the primary productivity or the photosynthetic activity of the algae. However, Zhirmunsky and Tarasov26 reported copper concentrations as high as 25 µg l⁻¹ from a seawater flooded volcano near Kurile Islands. Recently, Le Jeune et al.,27 studied the response of copper on planktonic micro-algal community. When they tested with 80 and 160 µg l⁻¹ copper concentrations, significant reduction in algal biomass was observed. They concluded that copper addition produced a direct effect on primary producers. The magnitude of copper effect also depended on initial composition of the biota and trophic alterations if any.

Analytical values of total dissolved copper and mercury in the coastal waters off Kalpakkam have been reported earlier by Selvaraj.15 His results show copper in the range of 72 - 2565 µg l⁻¹ and Hg in the range 64 -1513 µg l⁻¹ for surface seawater samples. According to Kureishy28, the values of copper and mercury reported by Selvaraj15 are very high when compared to the published values along coastal sites in the Bay of Bengal16,29. Such high levels of copper and mercury can potentially impact marine biota in a very significant manner. Recently, the values reported by Selvaraj15 have been countered by Satpathy et al.,17 who assayed seawater samples exclusively for copper. They reported an average of 44.5µg l⁻¹ of copper in the vicinity of MAPS. The values of copper reported by Satpathy et al.,17 also appear to be high as earlier and ongoing programmes like Bay of Bengal (BOB) programme and C-MARS have reported copper values in the range of 2 – 5 µg l⁻¹, for East coast of India. Martin and Richardson29 promoted the thesis of sequential approach as a reliable scientific means to conduct comprehensive assay regarding effluents discharged to marine environment. The approach involves the integration of data, observations, and information from laboratory and field studies into a comprehensive environmental assessment. We have followed the approach of Martin and Richardson29 in our investigation. It can be seen from Fig.3 that the average copper concentration from the 17 stations in the coastal waters of Kalpakkam observed during Sagar Purvi Cruise is ~0.72 µg l⁻¹. The mean copper value is below the values reported by C-MARS.9. However, during a recent sampling, the average copper concentration was estimated to be 2.54 µg l⁻¹ which is comparable to the C-MARS values. Hence, the earlier values reported15,17 for Kalpakkam site are significantly different.

Dynamic ecosystems like coastal marine environments have many interlaced food webs; alteration of any sub group will significantly affect the distribution of biota29. In marine environment, plankton exhibit greater ability to concentrate metals from water column and can be more useful biomonitors30. According to Diniz et al.,31, copper (II) ions and inorganic copper complexes are powerful inhibitors of phytoplankton activity even at very low
concentrations. Copper (II) ions show a high affinity for ligand sites at the cell membrane and once bound, they block the transfer of other essential ions to the cell. The more subtle aspects of metal toxicity in aquatic organisms can be more accurately estimated by examining the distribution of metals among the various aquatic zones. However, to understand the ecological significance of heavy metal toxicity, one must be able to relate the information on metal metabolism and its effects on the organism, the population, and the community. Moreover, the toxicity of copper to phytoplankton depends on the physicochemical form of the metal. Generally organic substances liberated by the phytoplankton are able to detoxify and complex copper. Surface-active forms of copper assume added importance due to their active role in the transport and biogeochemical cycling. According to Osterroht, et al., humic and fulvic acids are the background materials for the formation of organic copper complexes. The concentrations of copper (Fig. 3) showed little variation in distribution throughout the sampling area (0.5 – 2.1 µg l⁻¹), except for station 1 which showed marginally high copper value (5 µg l⁻¹). We have not done interrelations experiments between the copper concentration and phytoplankton activity in this investigation. However, the GPP data generated recently and the GPP data reported before the power plant went into operation are presented in Figure 2 and Table 5 for a comparative account and also to highlight that there has been no significant change in primary productivity over the last several years.

Apparently 25 years have elapsed since the power plant started operation, till date there is no convincing demonstration of the effect of dissolved copper on primary productivity in coastal waters. Table 5 describes the GPP values recorded at Kalpakkam site over two decades and Figure 2 illustrates GPP data recorded every month. The GPP ranged from 18 – 68 mg C m⁻³ h⁻¹. High GPP values were observed during September month wherein the sea coast is in transition phase (current changing from northerly to southerly). High GPP values were observed during August – September. It is likely that nutrient enrichment in the near-shore waters could have favoured high phytoplankton growth and productivity. Earlier workers have indicated that such algal blooms may be caused by upwelling phenomenon. However, in this context, we would like to highlight the importance of thermal discharges from the power station which also contain chlorine residuals. Poornima et al. concluded that power plant condenser outfall and heated effluents showed significant impact on the phytoplankton distribution when compared to the offshore coastal waters. Significant reduction in phytoplankton count and primary production was noticed up to the confluence zone of the heated effluent with coastal waters. Once the effluent flows in to the near shore waters and the surf region, the phytoplankton counts and productivity returned to normal values. This implies some damage to plankton during the passage through power plant cooling circuit. Saravanane et al. reported the recovery of phytoplankton population after transition through the cooling circuit. They also indicated that there was no prolonged or permanent damage to the phytoplankton during the transit. Cells surviving chlorination and heat are capable of quickly reestablishing pre-stress growth rates. Langford, Anupkumar et al. and Krishna kumar et al. emphasized that power plant effluent impacts or perturbations are highly localized and transient.

According to Yu et al., transitory changes might occur in the seawater in response to upwelling as a result of reversal of sea currents along Bay of Bengal coast. Such transitory changes occurring for a limited period make it difficult to detect the toxicity of a pollutant unless one adopts a method of continuous sampling. The mixing and dispersion effect in Bay of Bengal region is by combination of a strong river runoffs (Ganges, Brahmaputra, Mahanandi, Godavari, Krishna, Cauvery are perennial rivers joining the Bay of Bengal) and semi-diurnal tide along the coast. On the other hand, the western region of the bay is a sump for pollutants because of the major industrial activity and harbours. The normal structure and circulation of currents in the Bay of Bengal tend to prevent the mixing of the shallow coastal waters with rest of the sea, thus the pollutants may tend to concentrate along the coast. Although the present investigation was limited to Kalpakkam coast, if there is any concentration of heavy metals it must have reflected in the samples collected during the Sagar Purvi Cruise. Such an observation of high metal concentrations was not recorded in this study. Copper was dealt with in detail since the power plant condenser tubes are made of aluminum brass, a copper alloy. In support of our data we highlight here a recent metallurgical report by Das et al., who made an elaborate study of the in-service aluminum condenser tubes.
brass condenser tubes after 24 years of operation of MAPS. They reported that there is no significant corrosion of aluminum brass or release of copper from the condensers; the extent of corrosion of the condenser tubes is very marginal and it also had no significant impact on the mechanical properties of the condenser tubes.

Conclusion
Present investigation has provided a focused view of the status of a few important heavy metals in the coastal waters off Kalpakkam, East coast of India and also highlighted the available data on the levels of heavy metals in the Indian seas. The Sagar Purvi cruise data showed that the concentration of the studied heavy metals in the Indian seas was very small in comparison to some of the earlier published data. Primary productivity of the coastal waters was discussed in detail in light of the reports that heavy metals like copper could affect the productivity of the seawater. Besides, the comparative account of the primary production data before the power plant went into operation and after 25 years of operation also supports our view that the nuclear power plant has neither contributed to heavy metals release nor affected the marine biotic process in the near vicinity.

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