

## **Flood-associated Hydrobiological Changes in the Nearshore off Kochi, Along the Southwest Coast of India**

**<sup>1,2</sup>Albin K. J., <sup>1\*</sup>Jyothibabu, R., <sup>1</sup>Santhi Krishnan, S., <sup>1</sup>Sarath, S., <sup>1</sup>Alok K.T., <sup>3</sup>Gupta, G.V.M**

<sup>1</sup>CSIR- National Institute of Oceanography, Regional Centre, Kochi, INDIA

<sup>2</sup>Research Student, Bharathidasan University, Tiruchirappalli, INDIA

<sup>3</sup>Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Kochi, INDIA

\*Corresponding author: rjyothibabu@nio.org

### **Abstract**

This study presents how flood water transforms the hydrobiology of the nearshore waters close to estuarine inlets along the southwest coast of India, which are susceptible to significant freshwater discharge during the Southwest Monsoon (SWM) and depression events during the rest of the year. In the current study, coastal hydrography off Kochi that was acquired just before and during the flood event in August 2018 was compared with normal SWM conditions that prevailed in August 2014 and 2015. The SWM hydrography of August 2014 and 2015 revealed upwelling waters in the subsurface and a low saline lens in the top layer with a high concentration of chlorophyll-*a* ( $>3 \text{ mg m}^{-3}$ ). The impact of floodwater was found in August 2018, even at a distance of 7 km from the Kochi inlet, as the low saline plume that was 3 m thick before the flood, expanded to 8 m thick and occupied almost the entire water column during the flood. It was evident that the flood water decreased the total chlorophyll-*a* concentration and microplankton abundance in the study zone. During the typical SWM in August 2014 and 2015, the nano-size fraction of phytoplankton dominated the chlorophyll-*a* ( $>70\%$ ), but the micro-size fraction dominated (50 %) during the August 2018 flood time. All these suggest that the dilution effect of the flood could noticeably decline the phytoplankton biomass and abundance even at 7 km out to sea from the Kochi inlets, although it is unknown how this affects the higher trophic levels.

**Keywords:** Phytoplankton, flood water, river discharge, southwest coast of India, Arabian Sea

## 1. Introduction

Floods occur when precipitation accumulates on saturated soil in a region, or when water from a river, lake, or ocean overflow or disrupts drainage systems, allowing some of the water to leave its usual boundaries. Land-use changes such as deforestation and wetland destruction, changes in river courses or flood barriers such as drainage systems, and larger environmental problems such as climate change and sea-level rise have all been demonstrated to increase the intensity and frequency of floods globally (Junk et al., 2013; Padma 2018; Skariah and Suriyakala., 2022). Every year, the land mass along India's southwest coast gets significant monsoonal rainfall, the vast portion of which (~70%) occurs during the Southwest Monsoon (SWM; June to September) (Guhathakurta et al., 2015; Guntu et al., 2020). Massive rainfall in the foothills of the Western Ghats and adjacent landmasses in the region creates floods on occasion, and the large quantities of water associated with it predominantly flow westward through rivers and reaches the South-eastern Arabian Sea (SEAS) through the river/estuarine inlets (Jyothibabu et al., 2010). As a result, rainfall and freshwater discharge have a significant impact on the seasonal hydrographic features of estuaries of the Indian west coast, particularly during the SWM, and they transform into massive freshwater reservoirs during the flooding periods, losing their estuarine characteristics. As a result, the estuaries along India's west coast are referred to as monsoonal estuaries (Vijith et al., 2009).

The Kochi (Cochin) Backwaters (KBW), India's largest monsoonal estuary on the west coast, discharges its influx into the SEAS much faster during the SWM, with a flushing period of 2.8 days (Sivaprasad et al., 2013). During the SWM, the whole KBW transforms into a freshwater lake with very little saltwater intrusion, even in the inlet sections, due to the heavy river discharge (Madhuprathap, 1987; Jyothibabu et al., 2006). The increased flushing of the KBW during the SWM has a substantial influence on the hydrographic structure of the Kochi nearshore waters. As a result, a well-defined low salinity plume emerges in the nearshore waters, which tapers offshore (Anjusha et al., 2018; Karnan et al., 2020, Santhikrishnan et al., 2021). With the onset of the SWM rainfall, coastal upwelling also prevails in the nearshore waters of the SEAS (Banse 1968; Jyothibabu et al., 2010; Gupta et al., 2016; Anjusha et al., 2018; Karnan et al., 2020; Santhikrishnan et al., 2021). Many studies have shown that the low saline estuarine plume that fills the surface of the Kochi coastal waters during the SWM inhibits upwelled subsurface waters from surfacing (Jyothibabu et al., 2008; Anjusha et al., 2018; Karnan et al., 2020, Santhikrishnan et al., 2021). However, the whole coastal region remains eutrophic during the SWM because the surface low saline estuarine water also has a high concentration of nutrients (Anjusha et al., 2018; Karnan et al., 2020; Santhikrishnan et al., 2021).

Ecosystem-based studies since the 1960s have recorded a notable drop in zooplankton stocks in the KBW during the peak SWM, mostly due to the excessive freshwater discharge and the dilution they impart (Wellershaus, 1974; Madhuprathap., 1987; Jyothibabu et al., 2006, 2015). The massive freshwater discharge decreases the abundance and diversity of the zooplankton in the KBW in two ways (Wellershaus, 1974; Madhuprathap., 1987; Jyothibabu et al., 2006, 2015). The first process is the rapid flushing of the KBW within 2 days, which flushes away the mesohaline and euhaline zooplankton into the adjacent SEAS. The limnetic zooplankton community, which had just been introduced into the whole stretch of the KBW at that time, is extremely low in abundance due to the dilution effect of the massive precipitation that accumulates in the system. The hypothesis of flood water ‘dilution’ of the zooplankton abundance is rational because the multiplication time of most zooplankton is many weeks longer than the flushing duration of the KBW during the heavy freshwater discharge period (2.8 days) (Jyothibabu et al., 2015). However, because the production time of phytoplankton is significantly shorter (a few days) than that of zooplankton, floodwater dilution of the former has not been considered in past studies. Furthermore, the potential for significant floodwater flow to diminish phytoplankton densities in coastal waters along the west coast of India is still unclear. Taking flood occurrences, seasonal hydrography, and the plankton dynamics of the KBW and adjacent coastal marine waters into consideration, it is hypothesised that floodwater can reduce phytoplankton biomass and abundance in the nearshore waters along the southwest coast. To verify the idea, this study considered the recent hydrography data from the coastal waters of Kochi right before and during the 2018 flood event with typical hydrographical settings in the region during the SWM. The primary objectives of this study are to understand (a) the magnitude of the hydrographic changes that occur in the nearshore waters of the southwest coast of India during floods, and (b) how the flood-associated hydrographic transformation influences the nutrient regimes and phytoplankton community in the water column.

## **2. Sampling and Methods**

Monthly rainfall and the evolution of the seasonal rainfall pattern of the study region in 2018 are obtained from the Tropical Rainfall Measuring Mission (TRMM) rainfall database (<https://giovanni.gsfc.nasa.gov/>). The cloud cover data during the pre-flood and flood conditions were downloaded from an online source (<https://mosdac.gov.in/>). Information on the occurrence of flood from the study region since 1990 was obtained from the international disaster database (<https://public.emdat.be/data>). The flood events in this database are primarily based on the declaration of flood emergency by the concerned country/province. The *in-situ* data sets utilised in this study belong to two field sampling, one in 2014-2015 and the other in 2018-2019 (Figure 1). The first data

set was utilised to reflect normal hydrographic situations in the study region that did not experience floods during the SWM time. In this sampling, hydrographical data were gathered using a portable CTD from 4 locations along a cross-shore transect between 6 and 30 m depths. The second set of data, acquired in August 2018, was presented here to show the hydrographic conditions in coastal seas 7 km distant from the shore (12 m deep) (Figure 1). Two field sampling were made in August 2018: one before the flood [3<sup>rd</sup> August (BF)], and one during the flood [16<sup>th</sup> August (DF)].

A CTD profiler (SBE 43) was used to obtain vertical profiles of temperature, salinity, dissolved oxygen and chlorophyll-*a* (WET Labs ECO-AFL/FL) (Seabird electronics, USA; SBE 9plus). All the sensors were factory calibrated and the sensors of temperature, salinity, and DO have an analytical accuracy of  $\pm 0.0005$  °C,  $\pm 0.002$  and  $\pm 2\%$ , respectively and the chlorophyll-*a* sensor had a coefficient of determination of 0.8198 against laboratory measured values. It should be noted that there is some uncertainty between CTD-measured and laboratory-measured chlorophyll-*a* values because the former is found to be somewhat overestimated ( Roesler et al., 2017). To limit the possibility of overestimation, usually, the CTD data is corrected using the regression equation produced with laboratory-measured values versus wet lab sensor-based CTD values (Jyothibabu et al., 2015; Sarma et al., 2019). CTD temperature, salinity, and density data were used to calculate the Brunt-Vaisala frequency, a measure of water column stratification (Cushman-Roisin and Beckers., 2011). Water samples were collected in Niskin bottles, and dissolved oxygen (DO) and main macronutrients (NO<sub>3</sub>, PO<sub>4</sub>, and SiO<sub>4</sub>) were analysed using Winkler's technique and standard procedures, respectively (Grasshoff et al., 1983). A SKALAR SAN++ autoanalyser was used to do the measurements of nutrients (Detection limit: NO<sub>3</sub>  $\pm 0.027$   $\mu$ M, PO<sub>4</sub>  $\pm 0.009$   $\mu$ M and SiO<sub>4</sub>  $\pm 0.037$   $\mu$ M) with a precision of  $\pm 2\%$ ) using an automated flow analyser (autoanalyser, SKALAR SAN++). These measurements were taken at both the surface (0.5m) and bottom (9m). The total and size-fractionated Chl-*a* in water samples from the surface and bottom were determined using 0.5-1L water samples. For total Chl-*a*, water samples were filtered via a 0.22  $\mu$ m membrane filter. The determination of distinct phytoplankton size classes was achieved using the conventional stepwise filtration procedure (Jyothibabu et al., 2013; Albin et al., 2022). The chlorophyll-*a* samples so obtained were extracted in 10 ml of 90% acetone and measured fluorometrically (Trilogy, Turner Designs, USA, Detection limit-0.025  $\mu$ g L<sup>-1</sup>) (UNESCO, 1994). 1 L of water samples from the surface and bottom waters were obtained and preserved in a 3 % acidified Lugol solution for qualitative and quantitative investigation of microphytoplankton. One portion (500 ml) of the microphytoplankton samples was analysed in triplicate using an inverted microscope and the other portion (500 ml) using a FlowCAM (Karnan et al., 2017).

### 3. Results and discussion

#### 3.1. Hydrography

Kerala is popularly known as the ‘gateway of summer monsoon’, where the southwest monsoon sets in by June and continues till September (Krishnakumar et al., 2009). The monthly pattern of the wind is presented in Figure 2, which shows strong westerly/ northwesterly wind in the study region during the SWM. The basin-scale wind during the SWM is south-westerly in the eastern Arabian Sea, but the impact of the western Ghats (orographic effect) causes a change in the direction of the local winds prevailing closer to the Indian coastline. Due to the orographic effect of the western ghats the local winds prevailing closer to the Indian southwest coastline during the SWM is westerly/northwesterly (Hareesh Kumar and Anand (2016) and the references therein; Shanthikrishnan et al., 2021). Rainfall predominates in the study region during the SWM, particularly between June and August (Figure 3). Peak rainfall occurs in July, while there are considerable interannual changes owing to unique meteorological conditions. Nonetheless, the SWM accounts for the majority of the rainfall in the region (June to September). Figure 4 depicts the usual hydrographic setting of the study region during the SWM in response to the usual rainfall in 2014 and 2015. The first is coastal upwelling, which is characterised by the upslope of cool subsurface waters to the surface (Hareesh Kumar and Anand, 2016; Santhikrishnan et al., 2021). The second is a plume of low-saline estuary waters that eventually fill the surface layer of the nearshore waters, resulting in significant salinity stratification (Shanthikrishnan et al., 2021). A warmer and thicker (12 m) low salinity lens tapering offshore was visible in 2014, while such a thick low salinity plume was not visible in 2015. This is directly related to the large reduction in rainfall in August 2015 compared to 2014 (Figures 4a & c). According to recent research, the enhanced freshwater plume has the potential to impede the region's coastal upwelling process (Anjusha et al., 2018; Karnan et al., 2020; Santhikrishnan et al., 2021). In contrast, upwelling signatures were more evident in the study region in August 2015, since high saline and colder subsurface waters were seen even just below a thin low salinity lens. This might be the result of a combination of low rainfall in the study area and enhanced intensity of upwelling causative factors such as local winds and remote forcings. The upwelling process is well-established now, although its causative factors have undergone tremendous revision in recent decades. Local wind alone was attributed fully initially, then coastal currents were considered responsible, and now it is shown that both local winds and remote forcing through Kelvin and Rossby waves have major roles (Hareesh Kumar and Anand, 2016).

Table 1 depicts the retrospective analyses of flood events in Kerala from 1990 as a baseline. Since 1990, there have been 31 flood incidences in the region, with 26 occurring within the normal SWM

season. It should also be noted that some years experienced multiple floods during the SWM, while others did not. However, it is widely assumed that the frequency of floods in the study area has risen in recent years, making Kerala State vulnerable to flood-related disasters (Mirza., 2011). From June 1<sup>st</sup> to August 19<sup>th</sup>, 2018, the state of Kerala received 42 % more rain than the typical average (IMD, 2018). The cloud cover images in Figure 5 depict the meteorological condition that occurred in August 2018. The satellite images of daily cloud cover over the study region in August 2018 are conveniently classified as pre-flood (5<sup>th</sup> and 6<sup>th</sup>), flood (14<sup>th</sup> and 15<sup>th</sup>), and post-flood (24<sup>th</sup> & 25<sup>th</sup>). Pre-flood and post-flood circumstances had comparatively clear skies, however on August 14<sup>th</sup> and 15<sup>th</sup>, 2018, very thick cloud cover was prevalent over the study area, indicating considerably enhanced rainfall during these days. This cloud cover pattern is consistent with rainfall data from numerous sources, the torrential rainfall and flooding began on the 15<sup>th</sup> and lasted until the 17<sup>th</sup> of the month. During the 15<sup>th</sup> and 16<sup>th</sup> days, Pamba, Achankovil, Manimala, and Meenachil, four of KBWs six major tributaries, discharged 1.19 Billion Cubic Meters (BCM) of water, which was two times more than the carrying capacity of KBW (0.6 BCM) (Government of Kerala., 2018). This triggered a massive flood in the region, inundating the whole low-lying area near the KBW. Figure 6 shows satellite images of the KBW and neighbouring regions before and during the flood (BF and DF), which indicates that the tremendous flood water changed the KBW into a massive freshwater reservoir, which finally got flushed into Kochi's coastal waters over multiple tidal cycles (Figure 6). During a regular SWM, the whole KBW is flushed into Kochi's coastal waters in 2.8 days (Sivaprasad et al., 2013), however, the flushing is substantially slower during the Pre-Monsson period, which might last several weeks (3 weeks).

Our two samplings of Kochi coastal waters in August 2018, separated by 13 days, demonstrate the hydrographic structure of the study region before and during the flood (BF & DF). The flood caused a major change in hydrography in the location 7 kilometres offshore of the Kochi inlet (Figure 7; Table 2). The first data were gathered on August 3 (BF), when the coastal waters showed typical hydrographic structure for August during the SWM, with minor signals of upwelling in the subsurface and the existence of a 3-meter low salinity plume at the surface. Flood water affected the upper 8 metres of the water column during the second sampling on August 16<sup>th</sup> (DF). During the flood, the water column salinity on the surface dropped by over 6 units compared to the BF (Figure 7). The Brunt-Vaisala frequency parameter exhibited higher values before the flood when there was a limited surface low-saline plume and a wide underlying high-saline water mass (stronger stratification). Because the flood water influenced almost the entire water column, the stratification parameter value

in the surface layer was reduced during the flood, resulting in decreased vertical density gradients in the surface layers (Figure 7).

The water column temperature was found to be higher before the flood than during the flood, which is unexpected because low-saline waters are normally warmer than high-saline waters (Figure 7; Table 2). This reversal might be due to the cooling of the air induced by the high winds and rain during flood conditions. During the flood, all dams in rivers that drained into the KBW were opened, allowing water to enter the Kochi coastal waters and contribute to the cooling of the water column. Another possibility is that rainfall was cooler during the flood, and the rapid flushing of the floodwaters gives the freshwater less time to warm up before reaching the coast. The 23 °C cool water, which is often regarded as a marker of deep upwelling, remained at the deep layers throughout sampling both before and after the flood, indicating that upwelling was minimal in the study area. Earlier studies in Kochi and Alappuzha (50 km alongshore south of Kochi) coastal waters reported that upwelling strength is lower in August than in July and September (Karnan et al., 2017; Anjusha et al., 2018). This was evident in the dissolved oxygen level since hypoxic waters (indicative of upwelling) were only found in the near-bottom waters before and during the flood, indicating that upwelling was rather mild in the study region throughout the sample time. Furthermore, the massively increased flood water filled and oxygenated nearly the entire water column at the time (Figure 7; Table 2). This suggests that during the flood, the hypoxic waters were found at a deeper depth than before the flood (Figure 7).

Because of the high concentration of nutrients in the river discharge and the various non-point nutrient sources present in the KBW, the coastal waters off Kochi are exceptionally high in nutrients throughout the SWM (Martin et al., 2013; Gupta et al., 2016; Anjusha et al., 2018; Karnan et al., 2020). This characteristic of Kochi's coastal waters was found in the current investigation also as all macronutrients were significantly high during both BF and DF (Supplementary Figure 1). All nutrient concentrations in the surface layers increased during the flood (DF) compared to before the flood (BF); nitrate (BF - 4.14  $\mu\text{M}$ , DF - 5.55  $\mu\text{M}$ ), phosphate (BF - 0.3  $\mu\text{M}$ , DF - 0.62  $\mu\text{M}$ ), and silicate (BF - 20.73  $\mu\text{M}$ , DF - 29.62  $\mu\text{M}$ ) (Table 1). The overall concentrations of nutrients in the bottom depths were also considerably high during the observation: nitrate (BF-11.01  $\mu\text{M}$ , DF-5.08  $\mu\text{M}$ ), phosphate (BF - 1.55  $\mu\text{M}$ , DF - 1.29  $\mu\text{M}$ ), and silicate (BF - 15.69  $\mu\text{M}$ , DF - 24.61  $\mu\text{M}$ ).

### **3.2. Phytoplankton and the influence of the floodwater**

Phytoplankton biomass (chlorophyll-*a*) and abundance are high in the coastal waters of Kochi during the SWM, which is primarily linked to the high concentration of nutrients available there due to the coastal upwelling and the flux from the KBW (Anjusha et al., 2018; Madhu et al., 2010; Naqvi

et al., 2006). In August 2014 and 2015, the amount of chlorophyll-*a* in the surface and subsurface waters of Kochi was high, which is typical of the region due to the high levels of nutrients availability (Chl-*a* = av. 3.02 mg m<sup>-3</sup> and av. 1.84 mg m<sup>-3</sup>, respectively). During both years, nanoplankton contributed the majority of the chlorophyll-*a* concentration, followed by the micro and picoplankton (Figure 8; Table 2). During the 2018 August sampling (BF & DF), the total chlorophyll-*a* concentration was also markedly high in the study area. Significantly high Chl-*a* (4.65 mg m<sup>-3</sup>) was found in the surface waters before the flood (BF), which was reduced by more than half during the flood (2.30 mg m<sup>-3</sup>) (Figure 7). But only a marginal temporal variation in chlorophyll-*a* concentration was found in the bottom waters, where it was comparable between BF and DF. The depth-integrated chlorophyll-*a* concentration also showed a significantly high concentration during BF (42.41 mg m<sup>-2</sup>) compared to DF (11.34 mg m<sup>-2</sup>). The size-fractionated Chl-*a* concentration BF and DF showed a significant contribution of microphytoplankton to the total chlorophyll-*a* biomass in the surface waters (av. 61 ± 4%), which was unlike the earlier studies from the study area, all of which recorded the predominant contribution of nanoplankton during the SWM (Figure 8; Table 3). This change was caused by the high river discharge and the resultant low salinity that prevailed in the study area in August 2018 both during the BF and DF sampling. It is very clear in the monthly data from the study region that August 2018 has higher rainfall compared to August 2014 & 2015 (Figures 3 & 4).

Similar to the trend observed in the chlorophyll-*a* concentration (Table 2), the FlowCAM data of the microphytoplankton abundance in the surface waters BF was two-fold higher than DF (BF - 14088 ind. L<sup>-1</sup>, DF - 7710 ind. L<sup>-1</sup>). But in the subsurface waters, such a significant temporal variation in microphytoplankton abundance was not evident before the flood (BF - 4960 ind. L<sup>-1</sup>) and during the flood (DF - 5572 ind. L<sup>-1</sup>). During both samplings, *Rhizosolenia* and *Coscinodiscus* contributed to the microphytoplankton in the surface waters (Table 4). The FlowCAM-based aspect ratio of microphytoplankton showed the predominance of the needle-shaped (aspect ratio 0-0.39) individuals such as *Rhizosolenia* and *Thalassionema* during both sampling times, even though an increase in the contribution of the spherical-shaped (aspect ratio >0.6) was observed during the flood (Figure 9). The mean biovolume (MBV) of the microphytoplankton from FlowCAM analyses showed noticeably higher during the flood (av. 47063 ± 2275 μm<sup>3</sup> ind.<sup>-1</sup>) compared to before the flood (av. 6534 ± 252 μm<sup>3</sup> ind.<sup>-1</sup>) invariably conveying that relatively larger cells dominated during the former. In summary, it is clear that the total chlorophyll-*a* and the abundance of phytoplankton noticeably declined during the flood (Table 4). Hence, we propose that the observed variations in phytoplankton size classes, decline in biomass and abundance in the coastal waters of Kochi during the flood can be attributed to the enormous flood waters that significantly diluted the water column (Figure 7).



Past studies on phytoplankton community response to freshwater influx from different parts of the world have contrasting observations. Ciotti et al., (1995) investigated the impact of high rainfall and freshwater discharge on the coastal phytoplankton community along the Brazilian continental shelf. They observed an increment in phytoplankton standing stock in response to precipitation and associated freshwater influx. Similarly, Gomez et al., (2000) and Jagadeesan et al., (2021) proposed a case for riverine inflow along the Bay of Bengal and observed a positive response in chlorophyll-*a* concentration associated either with fresh water influx or in regions of low saline plume advection. Shafeque et al., (2021) observed a condition of favourable phytoplankton biomass response to precipitation along SEAS. All of the above investigations were conducted under conditions of normal freshwater inflow and have never dealt with massive flooding. There have been reports of increasing freshwater discharge causing a decrease in phytoplankton biomass in the northern Baltic Sea, however, the reasons given were more connected to phosphorus constraint than dilution (Wikner and Anderson., 2012). Ahmed et al., (2022) found a drop in phytoplankton biomass following significant rainfall events in Kuwait waters, however, they never considered the potential of dilution. Even though many studies have been conducted on the effect of precipitation and riverine discharge on phytoplankton, such studies never accounted for severe floods and associated massive freshwater influxes, which could dilute the phytoplankton along the adjacent coastal waters. Though phytoplankton dilution occurs during extreme flood circumstances, the characteristics normally do not continue for several days, and so the time available during the flood scenario is insufficient for the establishment of low saline-adapted plankton communities. We propose in this study that the idea that the plankton communities are more physically controlled in the Kochi backwaters (Wellershaus., 1974; Madhuprathap., 1987), appears to be valid for nearshore coastal waters also during intense flash floods. Though the abundance and biomass of phytoplankton have been reduced during the flood time, the nutrients associated with the low saline waters were found to favour the micro size fraction as there was an increase in their abundance and individual contribution to the total community biomass. All these aspects deserve a much more detailed investigation in the future considering the limited data presented in this study.

## **5. Conclusion**

Here, the Kochi coastal waters are used as a test case to demonstrate how massive flood water impacts the environmental and biological aspects of the nearshore seas of the southwest coast of India. The study, which used data from August in 2014 and 2015, revealed that the typical Southwest Monsoon in August is marked by a 3 m thick freshwater plume that tapers offshore and a high saline water mass in the subsurface with signs of coastal upwelling. Additionally, the entire water column

maintains noticeably high nutrient and chlorophyll-*a* concentrations, primarily due to nanoplankton contributions. On the other hand, the hydrography and the biological aspects of the area experienced substantial changes in August 2018, when a severe flood hit the area. The investigations carried out at a location 7 km from the shore comparing BF conditions (13 days before the flood) and DF in August 2018 revealed the following distinguishing characteristics. The low saline plume that typically covers the surface waters in the study location is about 3 metres thick, but during the flood, it rapidly thickened vertically and covered practically the whole water column. Total chlorophyll-*a* was observed to have significantly decreased during the flood (DF- 2.3 mg m<sup>-3</sup>) compared to the pre-flood state (BF- 4.65 mg m<sup>-3</sup>); a similar pattern could be seen in the quantity of microphytoplankton in both conditions. Microphytoplankton had a BF abundance of 14088 ind. L<sup>-1</sup>, which decreased DF to 7710 ind. L<sup>-1</sup>. All of these imply that the phytoplankton community has been significantly diluted by massive flood waters associated with depression episodes, which are frequent along the southwest coast of India, especially during the Southwest Monsoon.

### **Acknowledgement**

The authors thank the Director, CSIR- National Institute of Oceanography (CSIR-NIO), India for facilities and support. The authors thank the Director, CSIR- National Institute of Oceanography (CSIR-NIO), India for facilities and support. We also thank the Directors of the National Centre for Coastal Research (NCCR), Chennai and the Centre for Marine Living Resources and Ecology (CMLRE) Kochi for the facilities and funding. We thankfully acknowledge all participants of ORV Sagar Kanya cruise SK 351 and colleagues in the National Institute of Oceanography, India who helped in different stages of this work. The work was carried out in association with the SWQM/MEDAS programme of MoES. This is CSIR-NIO and CMLRE contributions ----- and -----, respectively

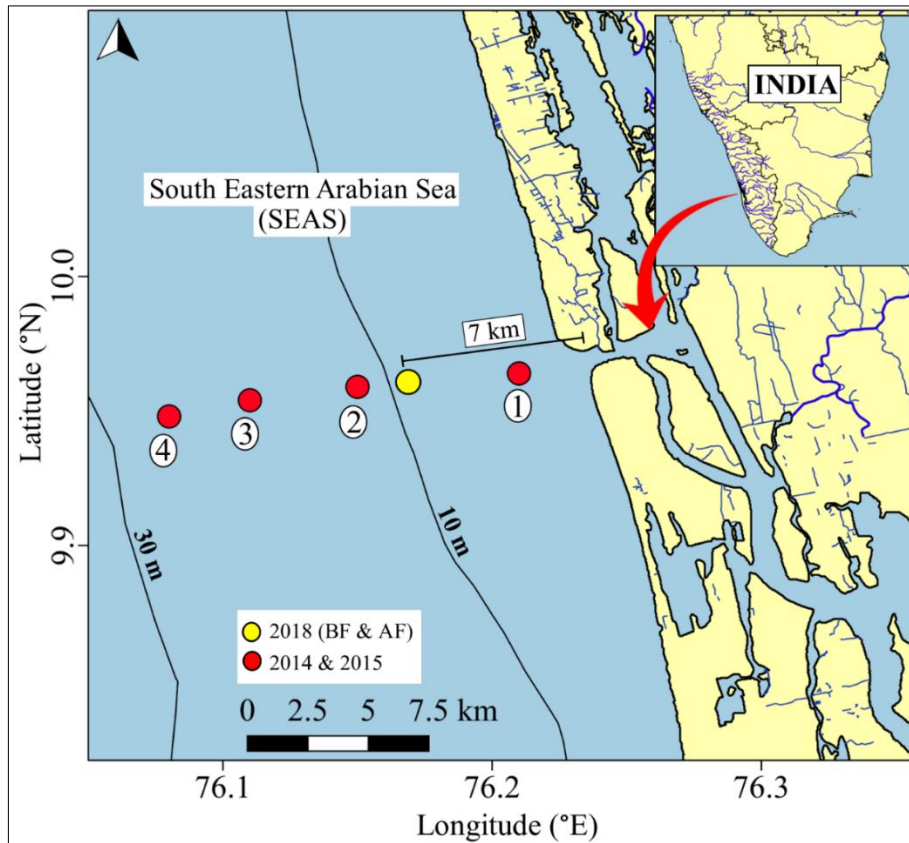
### **References**

- Ahmed, A., Al-Said, T., Madhusoodhanan, R., Naqvi, S.W.A., Sarkar, A., Fernandes, L., Thuslim, F., Al-Zakri, W., & Al-Yamani, F. 2022. Environmental impact of a series of flash flood events on a hypersaline subtropical system in the Northwestern Arabian Gulf. *Marine Pollution Bulletin*, 175, 113394.
- Albin, K.J., Jyothibabu, R., Alok, K.T., Santhikrishnan, S., Sarath, S., Sudheesh, V., Sherin, C.K., Balachandran, K.K., Devi, C.R.A., & Gupta, G.V.M. 2022. Distinctive phytoplankton size responses to the nutrient enrichment of coastal upwelling and winter convection in the eastern Arabian Sea. *Progress in Oceanography*, 203, 102779.
- Anjusha, A., Jyothibabu, R., & Jagadeesan, L. 2018. Response of microzooplankton community to the hydrographical transformations in the coastal waters off Kochi, along the southwest coast of India. *Continental Shelf Research*, 167, 111-124.

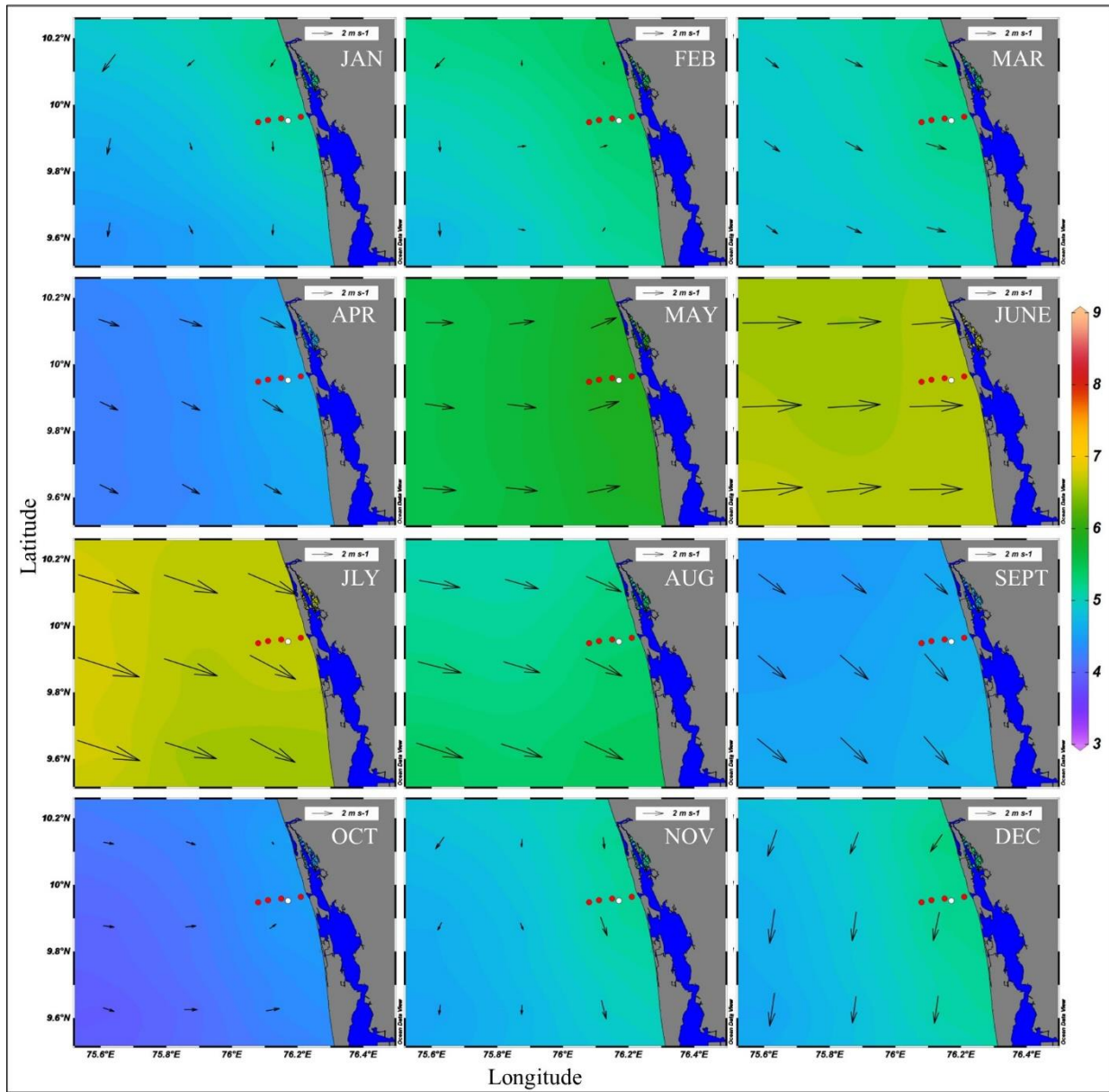
- Banse, K. 1968. Hydrography of the Arabian Sea shelf of India and Pakistan and effects on demersal fishes. In *Deep sea research and oceanographic Abstracts*. Elsevier, 45-79.
- Ciotti, A.U.M., Odebrecht, C., Fillmann, G., & Moller Jr, O.O. 1995. Freshwater outflow and Subtropical Convergence influence on phytoplankton biomass on the southern Brazilian continental shelf. *Continental shelf research*, 15(14), 1737-1756.
- Cushman-Roisin, B., & Beckers, J.-M. 2011. *Introduction to geophysical fluid dynamics: physical and numerical aspects*. Academic press.
- Gomes, H.R., Goes, J.I., & Saino, T. 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research*, 20(3), 313-330.
- Government of Kerala. 2018. *Additional Memorandum- Kerala floods-2018 1<sup>st</sup> August to 30<sup>th</sup> August, 2018*.
- Grasshoff, K., Ehrhardt, M., & Kremling, K. 1983. *Seawater Analysis*. In *Chemie, Weinheim*.
- Guhathakurta, P., Rajeevan, M., Sikka, D.R., & Tyagi, A. 2015. Observed changes in southwest monsoon rainfall over India during 1901-2011. *International Journal of Climatology*, 35(8), 1881-1898.
- Guntu, R.K., Rathinasamy, M., Agarwal, A., & Sivakumar, B. 2020. Spatiotemporal variability of Indian rainfall using multiscale entropy. *Journal of Hydrology*, 587, 124916.
- Gupta, G.V.M., Sudheesh, V., Sudharma, K.V., Saravanane, N., Dhanya, V., Dhanya, K.R., Lakshmi, G., Sudhakar, M., & Naqvi, S.W.A. 2016. Evolution to decay of upwelling and associated biogeochemistry over the southeastern Arabian Sea shelf. *Journal of Geophysical Research: Biogeosciences*, 121(1), 159-175.
- Hareesh Kumar P. V., Anand, P. 2016. Coastal upwelling off the southwest coast of India: observations and simulations, *International Journal of Digital Earth*, 9:12, 1256-1274, DOI: 10.1080/17538947.2016.1216614
- Indian Meteorological Department. 2018. *Rainfall over Kerala during monsoon season-2018 and forecast for next 5 days*.
- Junk, W.J., An, S., Finlayson, C.M., Gopal, B., Kvet, J., Mitchell, S.A., Mitsch, W.J., & Robarts, R.D. 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. *Aquatic sciences*, 75(1), 151-167.
- Jyothibabu, R., Madhu, N.V., Habeebrehman, H., Jayalakshmy, K.V., Nair, K.K.C., & Achuthankutty, C.T. 2010. Re-evaluation of ~paradox of mesozooplankton in the eastern Arabian Sea based on ship and satellite observations. *Journal of Marine Systems*, 81(3), 235-251.
- Jyothibabu, R., Madhu, N.V., Jayalakshmi, K.V., Balachandran, K.K., Shiyas, C.A., Martin, G.D., & Nair, K.K.C. 2006. Impact of freshwater influx on microzooplankton mediated food web in a tropical estuary (Cochin backwaters-India). *Estuarine, Coastal and Shelf Science*, 69(3-4), 505-518.

- Jyothibabu, R., Madhu, N.V., Maheswaran, P.A., Jayalakshmy, K.V., Nair, K.K.C., & Achuthankutty, C.T. 2008. Seasonal variation of microzooplankton (20-200  $\mu\text{m}$ ) and its possible implications on the vertical carbon flux in the western Bay of Bengal. *Continental Shelf Research*, 28(6), 737-755.
- Jyothibabu, R., Madhu, N.V., Martin, G.D., Aneesh, C., Sooria, P.M., & Vineetha, G. 2015. Waning of plankton food web in the upstream region of the Cochin backwaters during the southwest monsoon. *Indian J Geo-Mar Sci*.
- Jyothibabu, R., Mohan, A.P., Jagadeesan, L., Anjusha, A., Muraleedharan, K.R., Lallu, K.R., Kiran, K., & Ullas, N. 2013. Ecology and trophic preference of picoplankton and nanoplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India. *Journal of Marine Systems*, 111, 29-44.
- Jyothibabu, R., Vinayachandran, P.N., Madhu, N.V., Robin, R.S., Karnan, C., Jagadeesan, L., Anjusha, A., 2015. Phytoplankton size structure in the southern Bay of Bengal modified by the Summer Monsoon Current and associated eddies: Implications on the vertical biogenic flux. *J. Mar. Syst.* 143, 98–119.
- Karnan, C., Jyothibabu, R., Arunpandi, N., Albin, K.J., Parthasarathi, S., & Krishnan, S.S. 2020. Response of microplankton size structure to summer stratification, freshwater influx and coastal upwelling in the Southeastern Arabian Sea. *Continental Shelf Research*, 193, 104038.
- Karnan, C., Jyothibabu, R., Kumar, T.M., Jagadeesan, L., & Arunpandi, N. 2017. On the accuracy of assessing copepod size and biovolume using FlowCAM and traditional microscopy. *Indian Journal of Geomarine sciences*.
- Krishnakumar, K.N., Rao, G.P., & Gopakumar, C.S. 2009. Rainfall trends in twentieth century over Kerala, India. *Atmospheric environment*, 43(11), 1940-1944.
- Jagadeesan, L., Narasimha, R.D., Joseph, I., Parambil, A.M., Rachuri, V., Swarnaprava, B., & Kalathil, B.K. 2021. Role of riverine inputs, low saline plume advection and mesoscale physical processes in structuring the Chlorophyll-*a* distribution in the western Bay of Bengal during Fall Inter Monsoon. *Oceanologia*, 63(4), 403-419.
- Madhu, N.V., Jyothibabu, R., & Balachandran, K.K. 2010. Monsoon-induced changes in the size-fractionated phytoplankton biomass and production rate in the estuarine and coastal waters of southwest coast of India. *Environmental monitoring and assessment*, 166(1), 521-528.
- Madhupratap, M. 1987. Status and strategy of zooplankton of tropical Indian estuaries: a review. *B Plankton Soc Japan*.
- Martin, G.D., Jyothibabu, R., Madhu, N.V., Balachandran, K. K., Maheswari Nair, Muraleedharan, K. R., Arun, P. K., Haridevi C. K., Revichandran, C., 2013. Impact of eutrophication on the occurrence of *Trichodesmium* in the Cochin backwaters, the largest estuary along the west coast of India. *Environ Monitoring and Assessment* 185, 1237–1253. <https://doi.org/10.1007/s10661-012-2628-7>
- Mirza, M. 2011. Climate change, flooding in South Asia and implications. *Regional environmental change*, 11(1), 95-107.
- Naqvi, S.W.A., Naik, H., Jayakumar, D.A., Shailaja, M.S., Narvekar, P.V., 2006. Seasonal Oxygen Deficiency over the Western Continental Shelf of India. L. N. Neretin (Ed.), *Past and Present Water Column Anoxia*, 195–224.

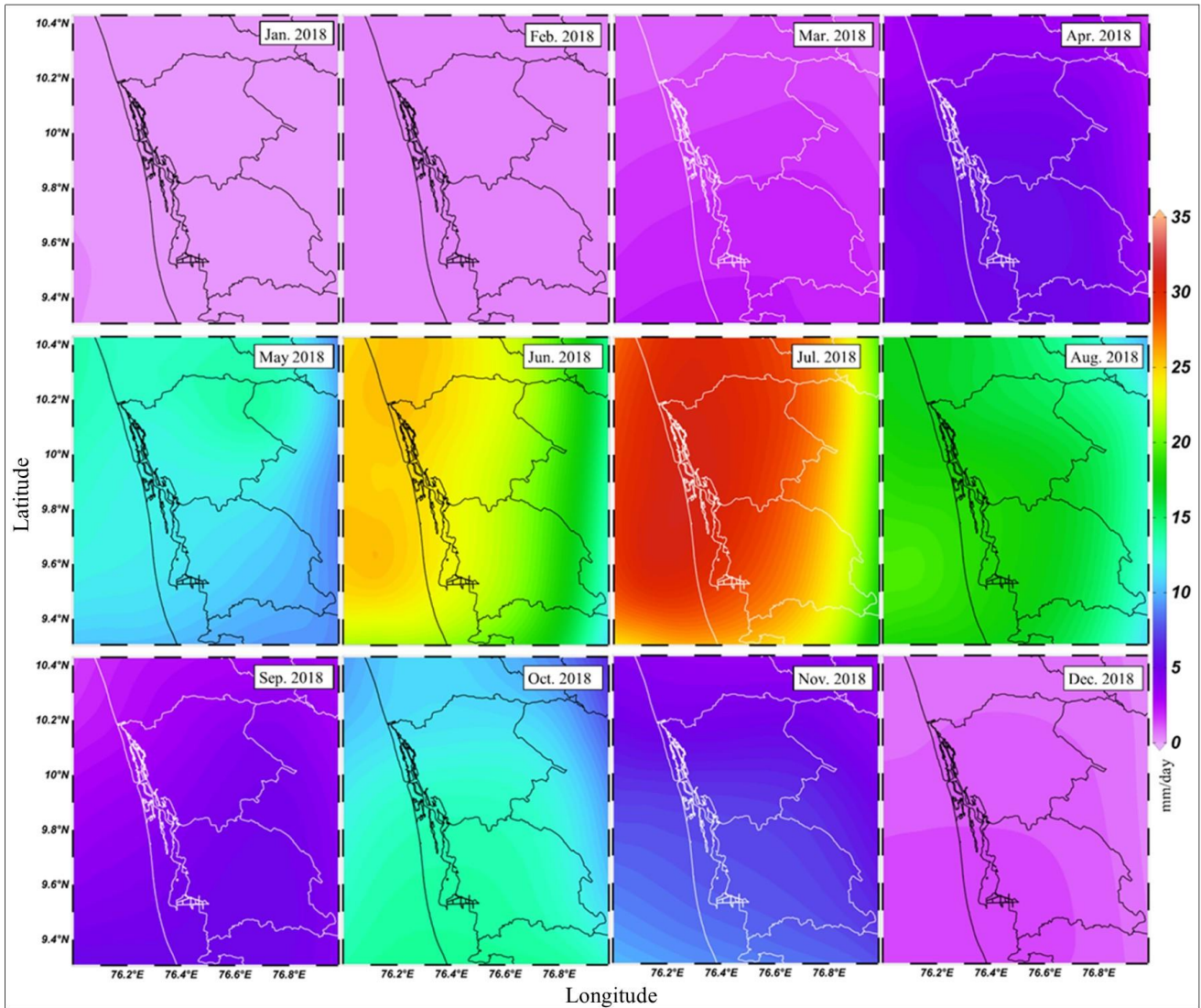
- Padma, T.V. 2018. Mining and dams exacerbated devastating Kerala floods. *Nature*, 561(7721), 13-15.
- Roesler, C., Uitz, J., Claustre, H., Boss, E., Xing, X., Organelli, E., Briggs, N., Bricaud, A., Schmechtig, C., Poteau, A., d'Ortenzio, F., 2017. Recommendations for obtaining unbiased chlorophyll estimates from in situ chlorophyll fluorometers: A global analysis of WET Labs ECO sensors. *Limnol. Oceanogr. Methods* 15 (2017), 572–585.
- Santhikrishnan, S., Jyothibabu, R., Albin, K.J., Alok, K.T., Karnan, C., Arunpandi, N., Camey, M.F., & Kumar, T.R.G. 2021. Biophysical implications of the freshwater influx over small spatial scale in the coastal waters along the southwest coast of India during the Southwest Monsoon. *Continental Shelf Research*, 214, 104337.
- Sarma, V.V.S.S., Patil, J.S., Shankar, D., Anil, A.C., 2019. Shallow convective mixing promotes massive *Noctiluca scintillans* bloom in the northeastern Arabian Sea. *Mar. Pollut. Bull.* 138, 428–436.
- Shafeeque, M., Shah, P., Platt, T., Sathyendranath, S., Menon, N., Balchand, A.N., & George, G. 2021. Effect of Precipitation on Chlorophyll-a in an Upwelling Dominated Region Along the West Coast of India. *Journal of Coastal Research*, 86, 218 - 224.
- Shivaprasad, A., Vinita, J., Revichandran, C., Manoj, N.T., Srinivas, K., Reny, P.D., Ashwini, R., & Muraleedharan, K.R. 2013. Influence of saltwater barrage on tides, salinity, and Chlorophyll a in Cochin Estuary, India. *Journal of Coastal Research*, 29(6), 1382-1390.
- Skariah, M., & Suriyakala, C.D. 2022. Land use/land cover changes (1988-2017) in Central Kerala and the effect of urban built-up on Kerala floods 2018. *Arabian Journal of Geosciences*, 15(10), 1-15.
- UNESCO., 1994. Protocols for the Joint Global Ocean Flux Study (JGOFS). Core Measurements. UNESCO, Paris 29, pp. 170.
- Vijith, V., Sundar, D., & Shetye, S.R. 2009. Time-dependence of salinity in monsoonal estuaries. *Estuarine, Coastal and Shelf Science*, 85(4), 601-608.
- Wellershaus, S. 1974. Seasonal changes in the zooplankton population in the Cochin Backwater (a South Indian estuary). *Hydrobiological Bulletin*, (1-2).
- Wikner, J., & Andersson, A. 2012. Increased freshwater discharge shifts the trophic balance in the coastal zone of the northern Baltic Sea. *Global Change Biology*, 18(8), 2509-2519.



**Figure 1** - The study area and sampling locations. The sampling locations in 2014 and 2015 in a cross-shore transect are presented in red circles. The yellow circle is the sampling point in 2018 before the flood (BF) and during the flood (DF). Blue lines represent the numerous rivers in Kerala (inset) and also the small canals and waterways associated with KBW.

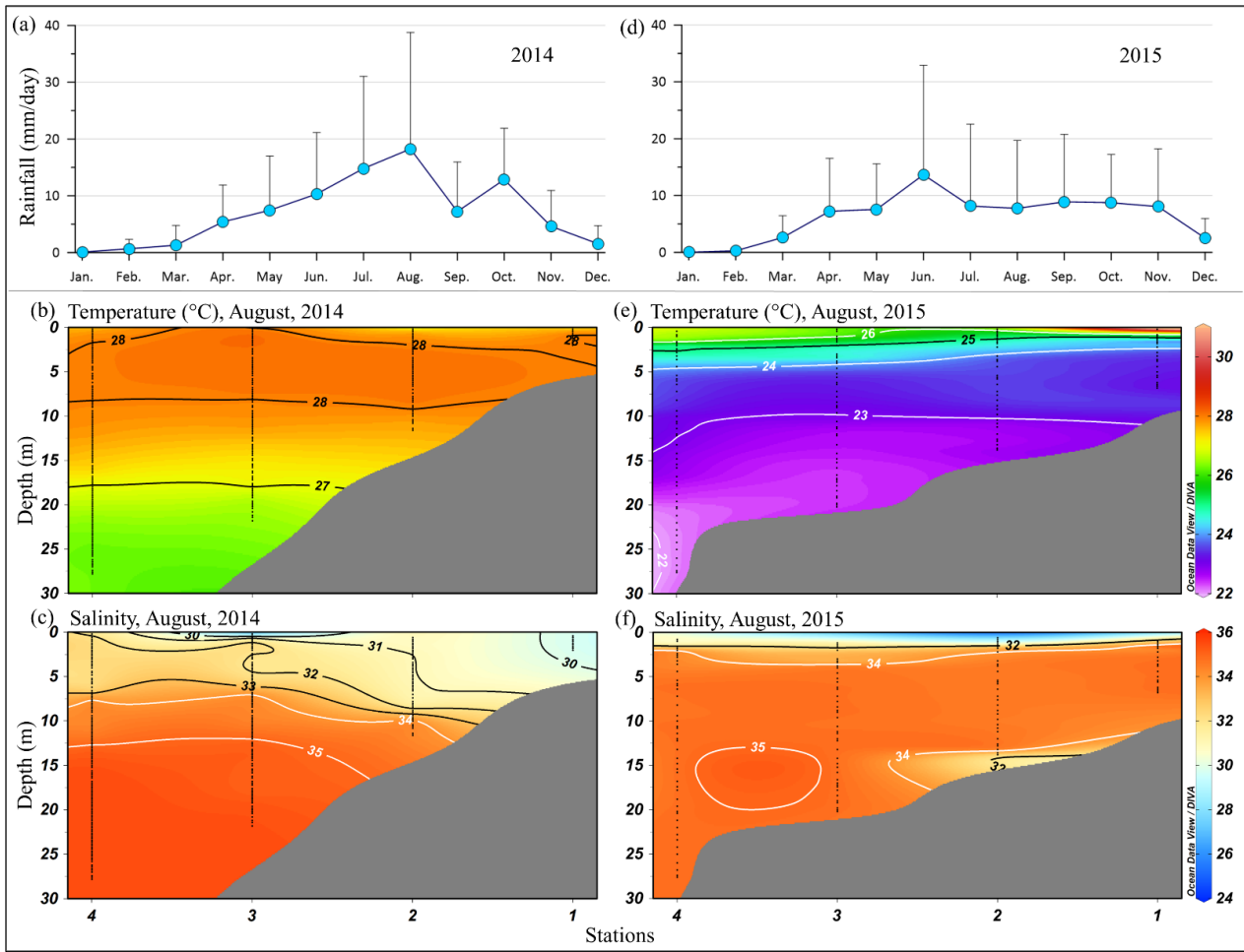


**Figure 2** - Monthly wind pattern in the study region in 2018. (Source: <https://giovanni.gsfc.nasa.gov/>). A clear increase in wind speed and the prevalence of westerly/northwesterly winds during the SWM are evident.

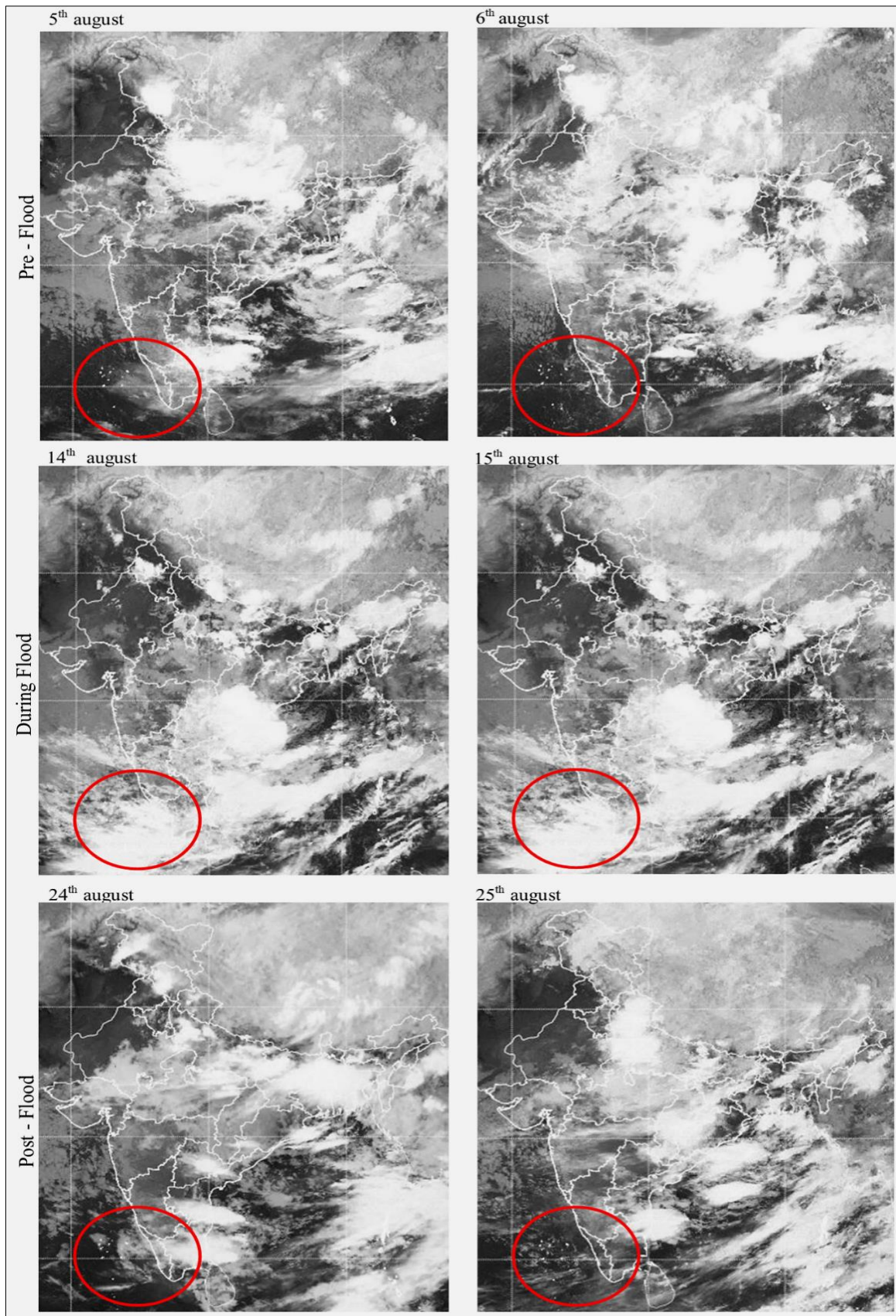


**Figure 3** - Monthly rainfall ( $\text{mm d}^{-1}$ ) and the evolution of the seasonal rainfall in the study region in 2018 (Source: <https://giovanni.gsfc.nasa.gov/>). A clear increase in rainfall during most of the SWM period (June- August) is visible.

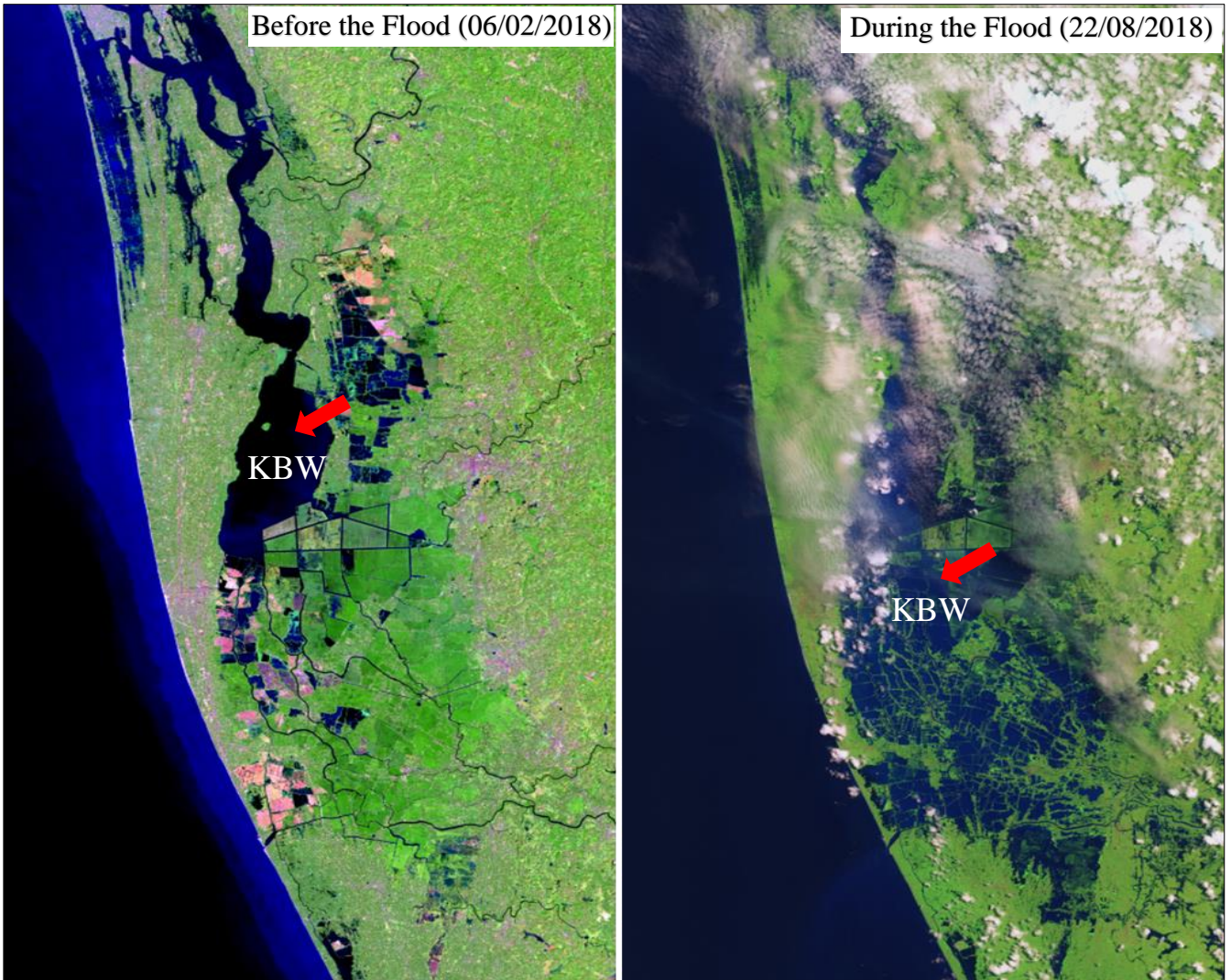




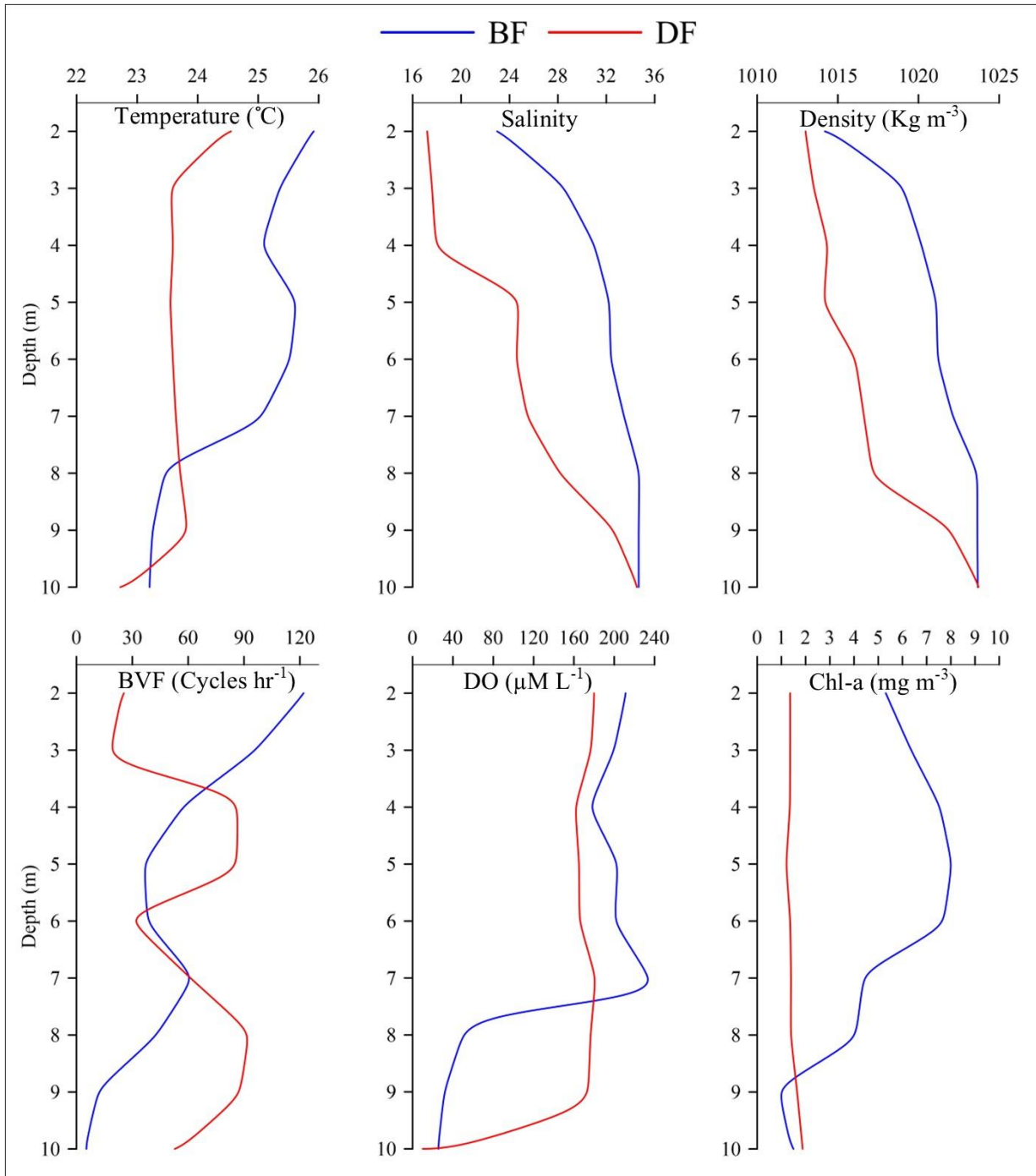
**Figure 4** - The pattern of rainfall in the study region (Source: <https://giovanni.gsfc.nasa.gov/>) and the hydrographical setting in the coastal waters of Kochi in August of the SWM in two years (2014 & 2015). Panels represent (a) rainfall and vertical distribution of (b) temperature and (c) salinity in the coastal waters of Kochi in 2014. (d), (e) and (f) are the corresponding variables for 2015. Stations 1 to 4 on the x-axis of the panels of the vertical distribution of temperature and salinity correspond to the locations in the cross-shore transects sampled in 2014 and 2015 as represented in Figure 1.



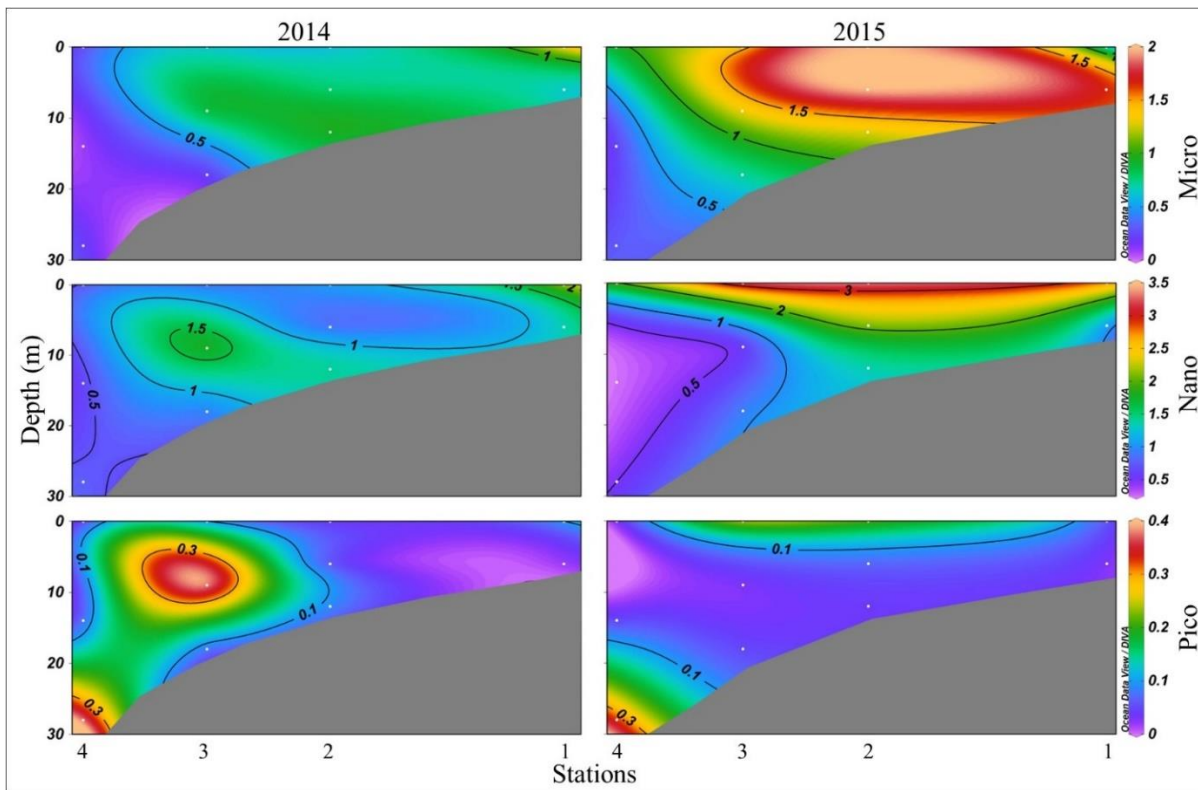
**Figure 5** - Cloud cover over the study region during three phases of the flood (pre-flood, during flood and post-flood) in August 2018. Significant cloud cover during floods suggests that heavy rainfall occurred at that time. The study region is demarcated by the red circle.



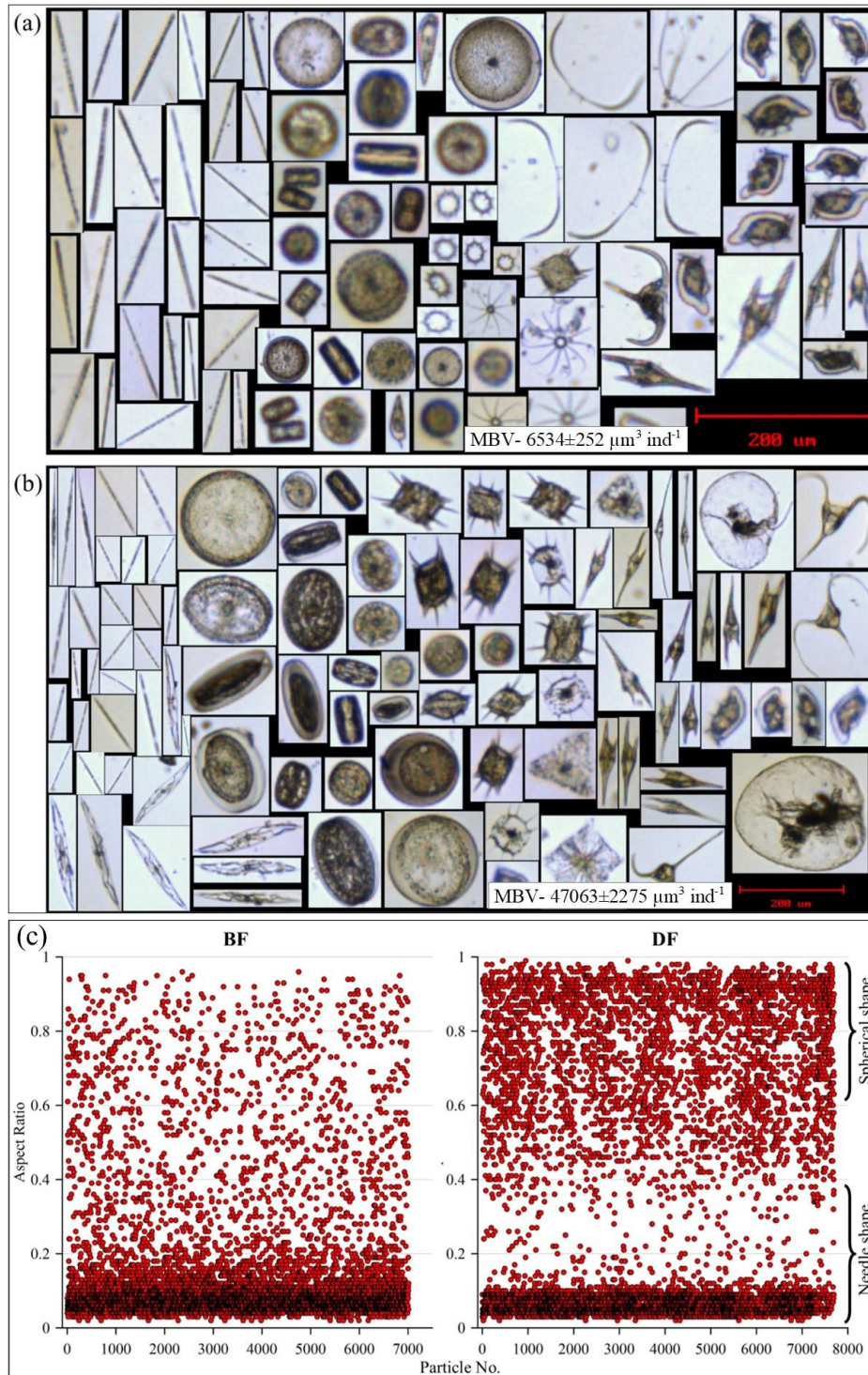
**Figure 6** - NASA earth observatory image of KBW (a) before and (b) during the flood of August 2018. This shows that the flood water has significantly impacted the KBW inundating the entire low-lying areas adjacent to it. The entire area becomes converted into a huge freshwater reservoir Image credit: <https://earthobservatory.nasa.gov/>



**Figure 7** - Vertical distribution of hydrographical variables BF and DF in August 2018 at the station marked in the yellow circle in Fig. 1. Brunt-Vaisala Frequency (BVF), Dissolved Oxygen (DO), chlorophyll-a (Chl-a)



**Figure 8** - The contribution of different size classes of phytoplankton chlorophyll-*a* in the study area during the typical SWM conditions as the case in August 2014 and 2015. The station located on the x-axis corresponds to red coloured sampling points Figure 1



**Figure 9** - Microphytoplankton composition from FlowCAM analyses (a) before the flood and (b) during the flood and (c) the aspect ratio of microphytoplankton in the surface waters before the flood (BF) and during the flood (DF) in August 2018. A significant contribution of needle-shaped (0-0.39) individuals is observed during both samplings while a noticeable increase in spherical-shaped cells (>0.6) was found in DF. MBV represents the mean biovolume of microphytoplankton.

**Table 1** - Flood incidences in Kerala along the southwest coast of India since 1990. The flood events were predominant during the SWM (Source: <https://public.emdat.be/data>).

<b>Sl. No.</b>	<b>Year</b>	<b>Period</b>
1	1991	10-12, June
2	1991	1 June to 9 July
3	1992	8 October
4	1992	10 November
5	1994	May - October
6	1996	21-25, October
7	1996	25 August to 1 September
8	1997	September
9	1998	August
10	1999	11 July to 3 August
11	2000	2-30, August
12	2001	4-16, July
13	2001	June
14	2002	21 June to 28 August
15	2002	10-16, October
16	2004	9-11, June
17	2006	25 May to 2 June
18	2007	22 June to 4 July
19	2007	16-20 July
20	2008	11 June to 21 July
21	2008	5-14, July
22	2009	July - September
23	2010	5-15, July
24	2013	12-27, June
25	2018	7-20, August
26	2019	14 July to 30 September
27	2019	19-23, October
28	2019	12-15, August
29	2020	1 <sup>st</sup> June to 18 <sup>th</sup> August
30	2021	1-30, June
31	2021	11-20, October

**Table 2** - The major hydrographical and biological variables before the flood (BF) and during the flood (DF) in August 2018. Surface and bottom values (in brackets)

Variables	BF	DF
Temperature (°C)	26.04 (23.21)	23.58 (22.72)
Salinity	22.97 (34.68)	17.7 (34.58)
DO (µM)	212.06 (25.94)	169.81 (4.95)
Nitrate (µM)	4.14 (11.01)	5.55 (5.08)
Phosphate (µM)	0.3 (1.55)	0.62 (1.29)
Silicate (µM)	20.73 (15.69)	29.62 (24.61)
Total chlorophyll- <i>a</i> (mg m <sup>-3</sup> )	4.65 (2.01)	2.3 (2.8)
Chlorophyll- <i>a</i> micro fraction (mg m <sup>-3</sup> )	2.54 (1.28)	1.49 (1.7)
Chlorophyll- <i>a</i> nano fraction (mg m <sup>-3</sup> )	1.4 (0.45)	0.57 (0.86)
Chl- <i>a</i> pico fraction (mg m <sup>-3</sup> )	0.06 (0.17)	0.05 (0.03)
Microphytoplankton abundance (No L <sup>-1</sup> )	14088 (4960)	7710 (5572)

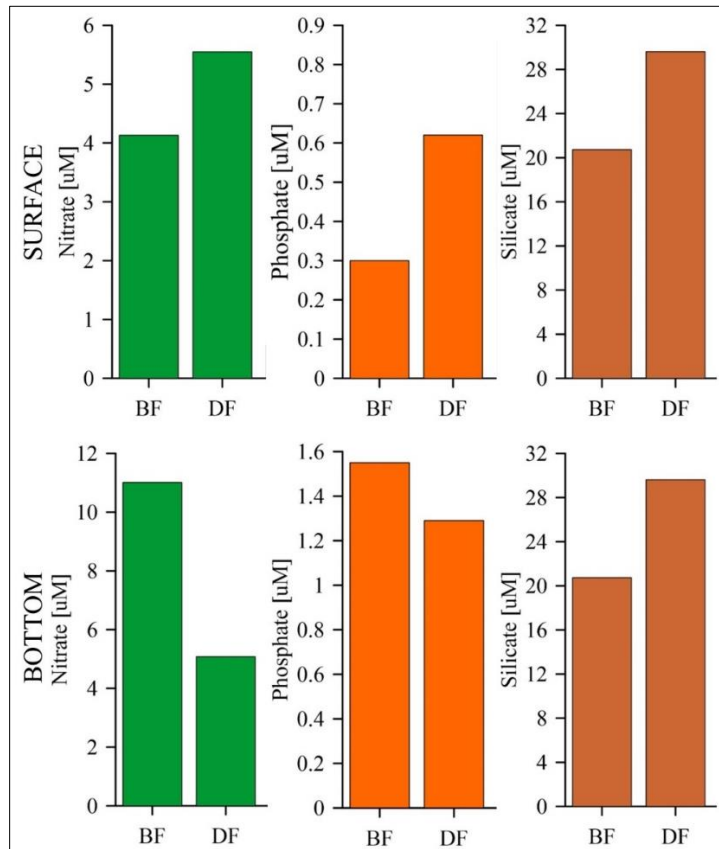


**Table 3** - The concentration of chlorophyll *a* (total and size-fractionated) in the inshore locations off Kochi recorded during the SWM in the literature.

Publication	Chlorophyll <i>a</i> (mg m <sup>-3</sup> )			
	Total	Micro	Nano	Pico
Madhu et al., 2010	av. 5.3	av. 0.85	av. 3.5	av. 0.54
Madhu et al., 2017	~6	~1	~5	~0.5
Anjusha et al., 2018	9.6	1.84	7.47	1.26
Santhikrishnan et al., 2021	av. 2.54	av. 0.72	av. 1.6	av. 0.2

**Table 4** - Microphytoplankton composition and abundance before the flood (BF) and during the flood (DF). Values of surface and bottom (in brackets) are presented.

Genus/ Species	BF	DF
	76	21
<i>Ceratium furca</i>	(-)	(-)
	46	362
<i>Ceratium</i> sp.	(60)	(141)
	830	8
<i>Chaetocerus</i>	(508)	(11)
	228	2524
<i>Coscinodiscus</i>	(1542)	(1806)
	406	12
<i>Dinophysis</i>	(358)	(73)
	10	31
<i>Guinardia</i>	(42)	(8)
	4	352
<i>Odontella</i>	(32)	(209)
	4	8
<i>Planktionella</i>	(6)	(2)
	-	17
<i>Pleurosigma</i>	(6)	(62)
	18	-
<i>Prorocentrum</i>	(6)	(-)
	30	12
<i>Protoperidinium</i>	(32)	(12)
	10884	934
<i>Rhizosolenia</i>	(482)	(266)
	64	-
<i>Silicoflagellates</i>	(152)	(5)
	1016	3103
<i>Thalassionema</i>	(358)	(858)
	198	70
<i>Thalassiosira</i>	(358)	(2117)
	274	256
Others	(506)	(2)
	14088	7710
Total	(4960)	(5572)



**Supplementary Figure 1** - The distribution of major macronutrients during the two phases of the flood (BF and DF) in August 2018.