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ANALYSIS OF TROPHIC STATE INDEX OF CHILIKA LAKE DURING PRE AND POST MONSOON SEASON USING *IN-SITU* AND LANDSAT-8 DATA OBSERVATIONS

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Abstract: The Trophic State Index (TSI) of Chilika Lake has been measured using the Secchi disk transparency as well as Landsat-8 OLI and LISS-III bands. The water quality parameters such as dissolve oxygen, pH, salinity, total suspended solid, turbidity, alkalinity, surface water temperature, ammonia, phosphate and nitrite of Chilika Lake are collected and measured from different sectors during pre and post monsoon period. The result indicates spatiotemporal variations of hydrological parameters during pre and post monsoon season. Different interpolation methods have been evaluated and the best method has been applied to create two dimensional water quality images of Chilika Lake. Analysis of water quality parameters indicated variation in physiochemical parameters with respect of different sectors. The pH of the entire lake is found to be alkaline and salinity of the lake changes from one sector to other due to influx of fresh water from eastern and northern rivers along with the distributaries of the Mahanadi river system. The analysis of LISS III and Landsat -8 images indicate the lake water is in eutrophic condition since the year 2006 to 2014. However, the average TSI values are comparatively less during the post monsoon period of 2013 and 2014. This may be due to the lake restoration program undertaken by Chilika Development Authorities.

Keywords: Interpolation, LISS-III, Landsat-8 OLI, Secchi disk transparency, Trophic state index.

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INTRODUCTION

Lakes are important sheltered sites of habitation for aquatic communities and highly productive ecosystem. There are many important factors responsible for changes in lake environment *e.g.* deforestation, intensive agriculture practices, unsustainable use of lake resources, industrial growth and sewage. Some natural changes resulting from physical, chemical, geological, biological factors and climatic changes also influence the essential character of the lake and hence the ecosystem. The degradation of world's lakes now is a serious global water resources issue. The major degradation impacts to lakes and reservoirs are caused by human activities in their surrounding drainage basins (Rast, 2009). Unpredictable climatic variations such as tidal waves, El Nino, cyclonic storms might also cause unpredictable changes through sediment loading, alteration of flushing rates of lakes and production processes (Fisher *et al.* 1972). The global circulation of precipitation is an important element for the functionality of the earth's ecosystem. Monsoon plays an important role for Indian climatic condition. Unpredictable monsoon has a wide range of direct and indirect impact on both the environment and the people of Lake Ecosystem. These impacts are closely interrelated with biodiversity, ecosystem goods and services, water balance and its availability, socioeconomic issues and health of the population. The impacts of unpredictable monsoon on biodiversity such as habitat loss and fragmentation invasive species, species exploitation, changes in water chemistry and environmental contamination etc. (Chase *et al.* 1999). The frequency and intensity of changing monsoon in India have serious consequences on the human, food security, financial, climate and lake ecosystems. The Chilika Lake was under constant ecological threat due to siltation and sedimentation through river runoff and land runoff in the catchment areas, leading to choking of the inlet mouth and poor interaction with the sea. Thus, siltation, choking of the out channel, shifting of the inlet mouth northwards, decrease in salinity, eutrophication followed by prolific growth of weeds, decrease in fish productivity, shrinkage of water area, loss of biodiversity and increase of human interference through prawn and aquaculture were identified as the major problems with the contemporary phase of lagoon transformation (Panda *et al.* 2008). Therefore, to monitor the health condition of the lake, the measurement of water quality parameter is essential. In this connection secchi disk transparency is an easy and useful cost effective measurement to find out the best indicator of water quality. Based on secchi disk transparency the trophic state index of lake can be generated. The trophic state index is used to categories lake in to the following four groups such as (i) oligotrophic (clear water), (ii) mesotrophic, (iii) eutrophic (turbid water) and (iv) hyper eutrophic (highly eutrophic). The trophic state index evaluates most of the lakes in a scale of 0 to 100. Trophic state index can also be derived from total phosphorus (Carlson 1977). Different lake management authorities for lake water quality assessment easily and widely use Secchi disk. The optical sensors of remote sensing satellites have been widely used to retrieve the water quality parameters since the spectral reflectance of water body is mainly influenced by the presence of substances in the water. Various spectral band combinations are used to find out the suspended sediment, chlorophyll content and clarity of water bodies. The Landsat series data has been widely used in different studies, as it is cost effective in terms of expenditure and effort for water sampling in the field (Khorram and Cheshire 1985, Lathrop 1992, Lavery *et al.* 2002, Brezonik *et al.* 2005). The main advantages of remote sensing satellite data is its ability to provide spatial measurement of different features across the large areas that is not possible with in-situ sampling. There are many optical sensors on satellites in orbit having similar spectral characteristics, which provide images over a length of time that can be analyzed to study the spatiotemporal changes. Among them Landsat has been extensively used for land based studies (Wilkie and Finn 1996) and less for inland lake water quality studies. It is mainly due to the spectral band resolutions of the Landsat thematic Mapper (TM) sensors. Short wave lengths are reflected by atmosphere and long wave lengths are absorbed by clear water, and the remaining amount of spectral energy reflected back to the sensor are used for aquatic feature detection. Despite of all these limitations, Landsat has been used successfully in aquatic studies for remote sensing of Secchi Disk Transparency (SDT) and suspended sediment concentration (Nelson *et al.* 2003). In the present study attempt is made to assess the trophic state index using Landsat-8 and LISS-III data along with *in-situ* water quality analysis of the entire Chilika Lake during the pre and post monsoon period.

EXPERIMENTAL

Study Area

The Chilika Lake is a natural lake located at 19° 28'- 19° 54' N latitude and 85° 06'- 85° 35'E longitude on the east coast of India in the Odisha state (Figure-1) and it is the largest brackish water lake in the subcontinent and one of the largest tropical lake of the world. The maximum length and width of the lake is 64 km and 22 km respectively. The average depth of the lake varies from 1.73 to 3.7 meters during rainy seasons and 0.93 to 2.6 meters during summer season. The number of mouth in the lake at present are three: one is called Muggarmukh near the village Arakhakuda, the other is Pallur Muhan and the third one is the opening of the new mouth opposite of the village Sipakuda (CDA, 2003). Due to its vast potential wealth of living and non-living resources and rich biodiversity, Chilika Lake is declared as a 'Ramsar site' under the Convention on Wetlands of International

Importance. The Chilika Lake plays an important role for socio economic development of the local people those who are directly or indirectly depend on the lake for their livelihood. It is one of the important tourist destinations of Eastern India due to its rich biodiversity, scenic beauty, Irrawaddy Dolphin, bird's sanctuary with beautiful small islands. Due to natural phenomena and anthropogenic activities, the lake environment over the past few decades has undergone some crucial changes. To conserve the lake ecosystem, the Government of Orissa through Chilika Development Authority (CDA), monitored various multi-disciplinary and multi-dimensional developmental activities with an overall objective to protect the lake's eco-system with all its genetic diversity and to restore its past glory.

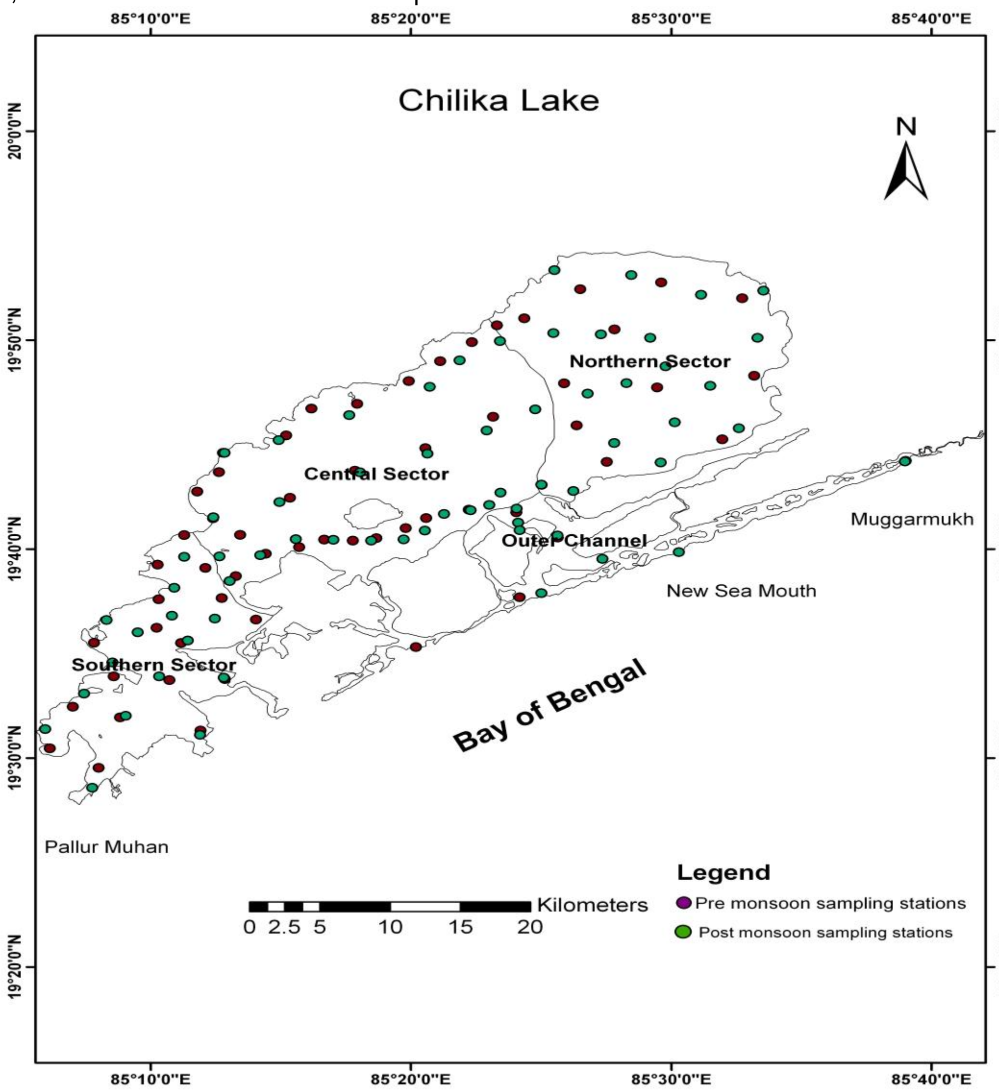

Figure 1. Map of Chilika Lake showing sampling stations

Field Data Collection and Analysis

Observations on water quality parameters such as Secchi disk depth, dissolve oxygen (DO), surface water temperature, salinity, pH, alkalinity, turbidity, total suspended solid (TSS) and water nutrients (ammonia, nitrite and phosphate) are collected from 4 different sectors during pre and post monsoon season of 2014 covering entire lake with the help of Global Positioning System (GPS). During sample collection in the lake, necessary precautions were taken to collect water samples. The Sechhi disk depth, pH and temperature were analyzed on the spot of the sampling station. Chemical analysis of different water quality parameters are carried out following the standard methods as prescribed by MOES, Govt. of India (revised draft, 2011) for coastal water quality measurements (COMAPS) programme.

Methodology

A Sechhi disk (20 cm) diameter metal disk in black and white colour, is attached to a measured line and lowred in to lake until it can go longer to be seen (Figure 2). The depth at which Secchi disk disappears is known as the Secchi disk transparency. The trophic state index (TSI) can be computed from Secchi disk transparency and total phosphorus. Trophic state index deviation (Carlonson, 1977; Kratzer and Brezonik, 1981) is important index for lake transparency assessment. Carlson has explained the relationship between TSI and Secchi disk transparency in 1977. Since then, many researchers have used the Sechhi Disk Transparency (SDT) and TSI relationship in lake water studies (Paukert and Willis 2003; Galas 2003; James 2008; Bio *et al*. 2008; Navarro *et al.* 2009). The TSI and SDT relationship is provided in equation 1.

$$TSI(SDT) = 10(6 - \ln SDT/\ln 2) \quad (1)$$

Many investigators based on salinity, nutrients and chlorophyll (Gupta *et al*. 2008, Muduli *et al.* 2012) carry sector wise zonation of lakes. In the present study, the same zonations have been considered for further investigation. The analysis of TSI is carried out from in-situ observation as well as from the satellite data. Total number of 59 and 65 points are used to generate the TSI from the *in-situ* observations during the pre and post monsoon season respectively. The lake water can be classified based on TSI range that is given in table-1 (Fuller and Minnerick 2007). In the present study, an attempt is made to develop an algorithm to derive STD for Chilika Lake using spectral bands of Landsat-8 OLI. The ground truth measurements were carried out synchronous to Landsat-8 pass. The relationship between ratio of the Landsat-8 OLI band (band 3:band 4) and Secchi Disk Transparency (SDT) is presented in Figure 3. The analysis has been carried out in linear, exponential, logarithmic, polynomial, power and moving average mode. It is found that the relationship exhibits a better coefficient of determination (R^2= 0.7) in exponential form which is presented in equation 2. Since, the Landsat-8 OLI band 3 and band 4 are equivalent to Linear Imaging Self Scanning (LISS- III) band 2 and band 3, the equation 2 can be used to retrieve the Secchi disk transparency using LISS-III data. In absence of Landsat-8 data before the year 2012, the LISS III data was used to retrieve the SDT.

$$SDT = 0.013\exp^{2.570(OLI\ BAND3/\ OLI\ BAND4)} \quad (2)$$

Figure 2. Use of Secchi disk in Chilika Lake

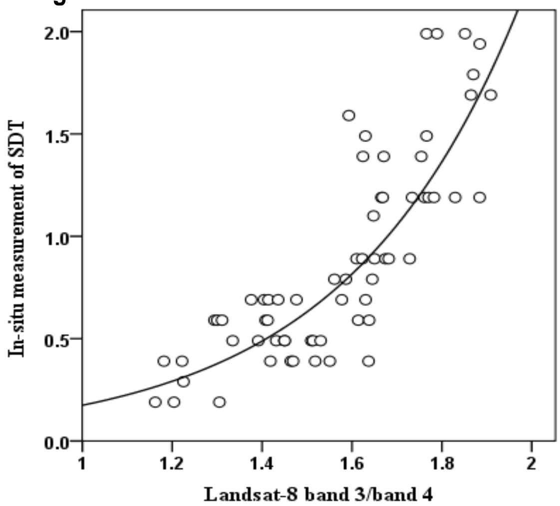

Figure 3. Scatter plot showing relationship between the *in-situ* measurement of SDT and band ratio of Landsat-8

In this study field, data is interpolated to create 2-D images. Different interpolation methods (table 2) have been evaluated and the best method is adopted to generate 2-D images. To find out the closeness of the observed and interpolated values the absolute difference (AD) and absolute percentage difference (APD) have been verified using randomly 11 selected points. The AD and APD values are computed using the following equations (Melin *et al.* 2007).

$$AD = (1/N)\sum_{i=1}^{i=N} |yi - xi| \qquad (3)$$

Table 1. Lake trophic state and Carlson TSI

Lake trophic state	Carlson TSI
Oligotrophic	<38
Mesotrophic	38-48
Eutrophic	49-61
Hypereutrphic	>61

$$AD = 100 * (1/N)\sum_{i=1}^{i=N} (|yi - xi|)/xi \qquad (4)$$

Where, x, y and N represents observed value, interpolated value and number of points respectively. The satellite derived TSI over pre and post monsoon season from the year 2006 to 2014 have been generated to assess the trophic status of the lake over a decade.

RESULTS AND DISCUSSION

The water quality parameters such as Secchi disk transparency, DO, pH, salinity, total suspended solid (TSS), turbidity, surface water temperature, alkalinity, trophic state index (TSI), phosphate, nitrite and ammonia are analyzed during the pre and post monsoon seasons. These are the important parameter of the water body through which lake ecosystem and its health status can be assessed (Nayak *et al.* 2004; Gupta *et al.* 2007; Bramha *et al.* 2008; Sharma *et al.* 2010). The above water quality parameters are collected during 6 to 8 June and 28 to 30 October 2014. Since one of the objectives of the study is to explain how best the various interpolation methods explains the distribution of environmental parameters, this study compares several methods of interpolation techniques (kriging, inverse distance to power, minimum curvature method, modified shephards method, natural neighbor, nearest neighbor, polynomial regression, Radial Basis Function, triangulation with linear interpolation, moving average and local polynomial). The best interpolation technique is identified based on the closeness of the values collected in the field with that of interpolated image. The *in-situ* data pertaining to Secchi disk transparency have been used to evaluate the above mentioned interpolation techniques and the output-interpolated images have been presented in Figure 4. The statistical outputs of AD and APD values between observed and interpolated values of selected points have been presented in Table 2. It has been found that the kriging provides the best-interpolated image with reference to its shape and range of interpolated values. Though the AD and APD values in case of radial basis function, minimum curvature and modified Shepherd's method are closer to AD and APD values of kriging but the interpolated image shows out of range values in case of all the above mentioned methods. Therefore, in the present analysis, kriging interpolation technique is applied for interpolation of *in situ* observations. The *in situ* interpolated images of Secchi disk transparency, dissolved oxygen, pH, salinity, alkalinity, turbidity, total suspended solid, surface water temperature, ammonia, phosphate, nitrites, TSI, are shown in Figure 5 and Figure 6.

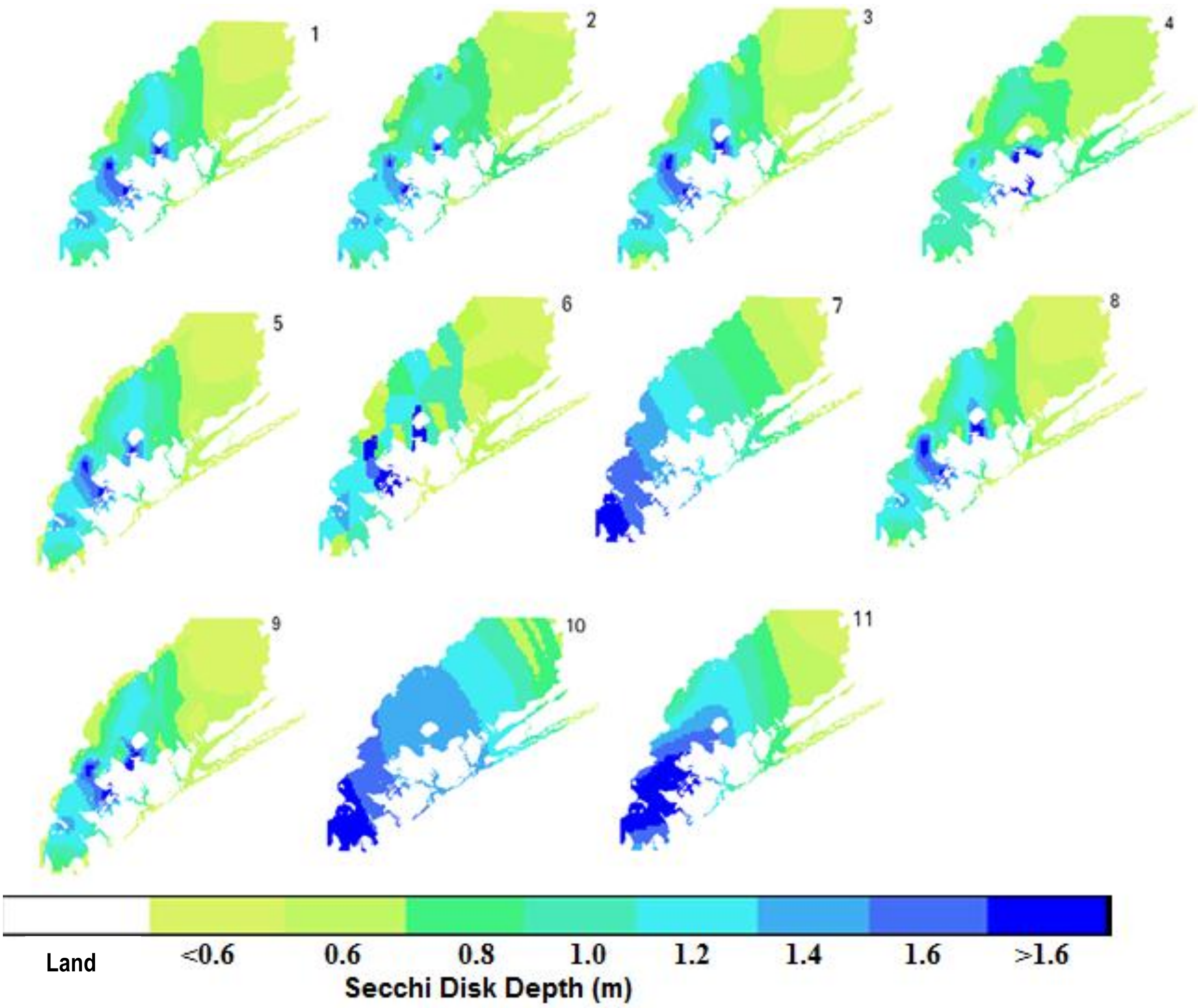

Figure 4. Interpolated images using *in situ* Secchi disk transparency data: The interpolated images using *in situ* Secchi disk transparency data: 1. Kriging, 2. Inverse distance to power, 3. Minimum curvature method 4. Modified shephards method, 5. Natural Neighbor, 6. Nearest Neighbour 7. Polynomial regression, 8. Radial Basis Function, 9. Triangulation with linear interpolation, 10. Moving Average and 11. Local Polynomial.

Table 2. Values of absolute difference, absolute percentage difference between observed and interpolated value

S.No.	Methods	AD	APD
1.	Krigging	0.227760545	22.83422723
2.	Inverse Distance to Power	0.272821818	29.59266349
3.	Minimum Curvature	0.240917273	24.40741998
4.	Modified Shephards Method	0.247656455	24.25909348
5.	Natural Neighbour	0.319841636	32.42184905
6.	Nearest Neighbour	0.294909091	27.65044347
7.	Polynomial Regression	0.305083545	29.85062683
8.	Radial Basis Function	0.252661000	25.36038759
9.	Triangulation with Linear Interpolation	0.304231273	29.62925263
10.	Moving Average	0.409410818	46.96797268
11.	Local Polynomial	0.299387545	28.46374729

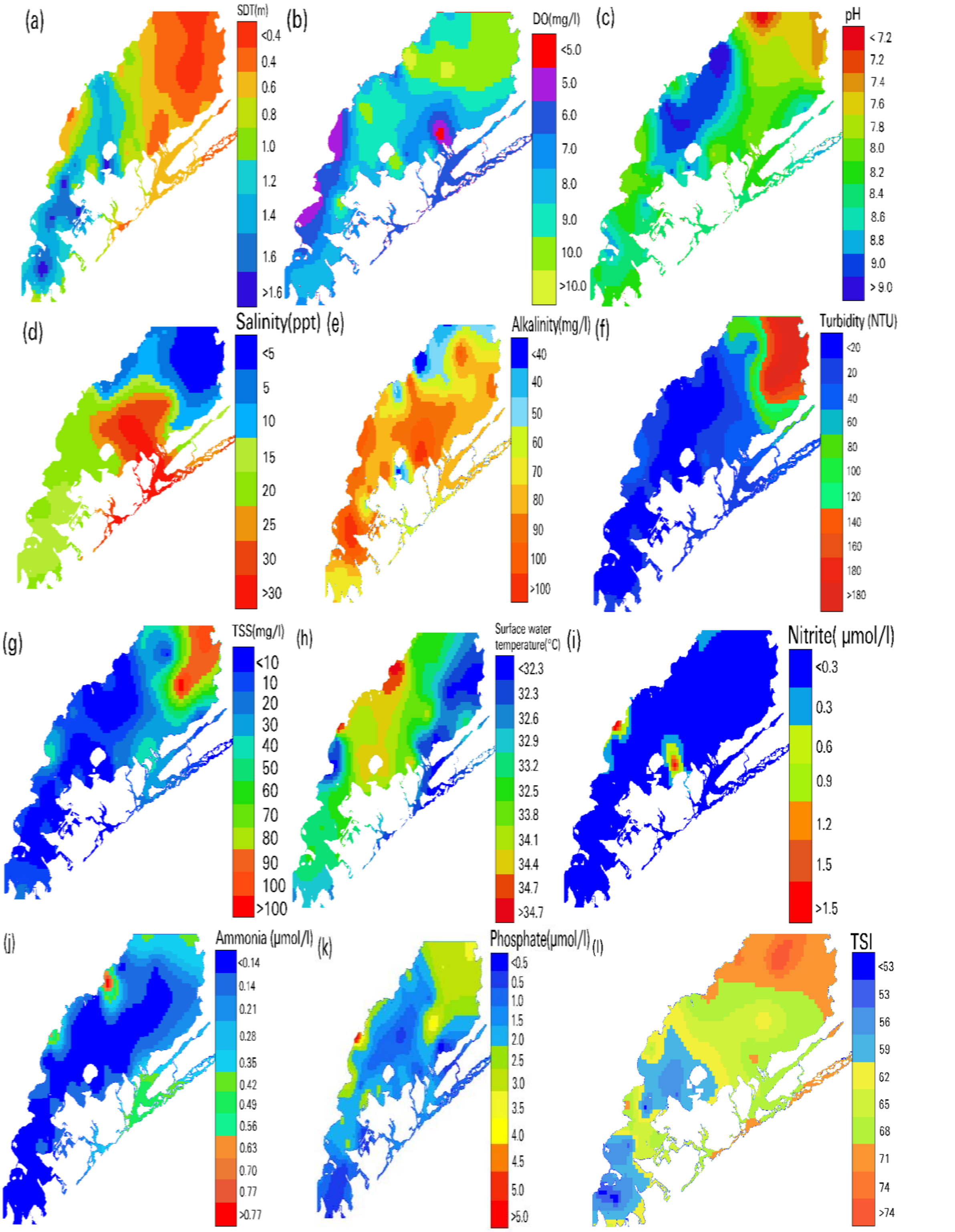

Figure 5. **Pre-monsoon interpolated images *in-situ*** (a) Secchi Disk Transparency (SDT), (b) DO, (c) pH, (d) Salinity, (e) Alkalinity, (f) Turbidity, (g) TSS, (h) Surface water temperature, (i) Nitrite, (j) Ammonia, (k) Phosphate and (l) Trophic State Index during pre-monsoon 2014.

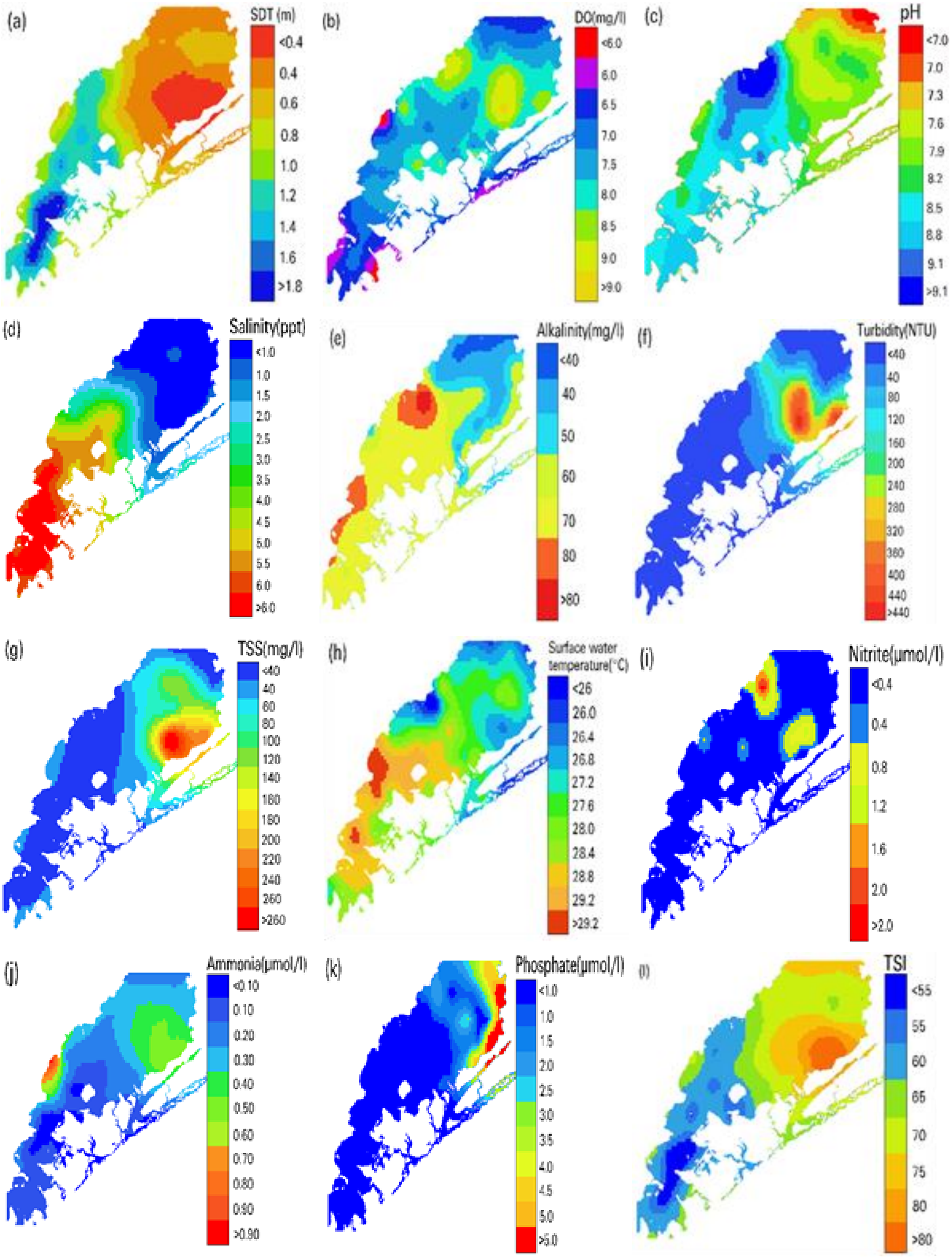

Figure 6. Post-monsoon interpolated images *in-situ* (a) Secchi Disk Transparency (SDT), (b) DO, (c) pH, (d) Salinity, (e) Alkalinity, (f) Turbidity, (g) TSS, (h) Surface water temperature, (i) Nitrite, (j) Ammonia, (k) Phosphate and (l) Trophic State Index during post-monsoon 2014.

Secchi Disk Transparency (SDT): The pre monsoon period SDT image (Figure 5a) shows maximum to minimum variation of SDT ranging from 1.69 m, 1.39 m, 0.69 m and 0.34 m in southern sector, central sector, outer channel and northern sector respectively. The pre-monsoon period average value of SDT is around 0.85 m. In the post monsoon period SDT image (Figure 6a) shows maximum to minimum variation of SDT in the range from 1.99 m, 1.5 m, 0.69 m and 0.2 m in southern sector, central sector, outer channel and northern sector respectively. The post monsoon period average value of SDT was found to be 0.87 m.

Dissolve Oxygen: Concentration of dissolve oxygen in the water body is a significant parameter for biological livelihood and important for water quality assessment. Oxygen depletion is a critical condition for aquatic life and adversely affects their life. Determination of oxygen is very important for aquatic life, their health status and indicate the concentration of pollution by organic matter, destruction of organic substances and the level of self-purification of water (Champan and Kimstatch, 1996). In the present study for estimation of dissolve oxygen in the water samples Winkler's method have been used. The pre monsoon period DO image (Figure 5b) shows maximum to minimum variation of DO ranging from 9.79 mg/L to 6.89 mg/L, 10.43 mg/L to 4.73 mg/L, 9.43 mg/L to 5.02 mg/L and 6.47 mg/L to 3.8 mg/L in northern sector, central sector, southern sector and outer channel respectively. The pre monsoon period average value of DO is around 7 mg/L. In the post monsoon period DO image (Figure 6b) shows maximum to minimum variation of DO in the range from 9.98 mg/L to 6.32 mg/L, 9.02 mg/L to 5.02 mg/L, 7.4 mg/L to 5.87 mg/L and 9.02 mg/L to 5.7 mg/L in northern sector, central sector, southern sector and outer channel respectively. The post monsoon period average value of DO was found to be 7.34 mg/L.

pH: The pH in the water body is considered a very important factor in the brackish water lake. The distribution and decomposition of hydrophytes in the lake depend on the pH of the water. The pH of entire Chilika Lake is alkaline. The pH of the lake is measured by (multi kit-340i) pH meter. The range of the pH slightly fluctuates between 7.12 to 9.28 during the pre-monsoon period. The pH image (Figure 5c) shows the highest pH values are found in central sector followed by southern sector. In the outer channel pH values is more than 8.17 and in the northern sector pH value is around 7.12. In the post monsoon period pH image (Figure 6 c) shows maximum to minimum amount of pH variation ranging from 8.22 to 6.58, 8.58 to 8.1, 9.57 to 7.45 and 8.39 to 7.78 in northern sector, southern sector, central sector and outer channel respectively. The pre and post monsoon period average value of pH was found to be 8.39 mg/L and 8.09 mg/L respectively.

Salinity: Salinity plays an important role for brackish water lake ecology. It effects on biodiversity distribution of flora and fauna. In particular, fauna distribution in the brackish water lake ecosystem depends on the amount of salinity. The salinity of the Chilika Lake is influenced by influx of fresh water from the distributaries of Mahanadi river (Daya and Bhargavi) discharges during different seasons, wind action and the sediment deposit at mouth of the lake. In this study salinity was measured by multi parameter water quality measurement instrument (multi kit-340i) during the in-situ data collection. The pre and post monsoon season salinity distribution of the Chilika Lake is highly variable. The salinity ranges during pre and post monsoon was observed as 1.1 - 30.5 ‰ and 0.1 - 6.7 ‰ respectively. The pre monsoon period salinity image (Figure 5d) shows maximum to minimum variation of salinity in the range from 30.5‰ to 22.4‰, 28.2‰ to 6.5‰, and 16.7‰ to 12.5‰ and 27.2‰ to 1.1‰ in outer channel, central sector, southern sector and northern sector respectively. In the post monsoon period salinity image (Figure 6d) shows maximum to minimum variation of salinity ranging from 6.71‰ to 5.4‰, 6.1‰ to 0.2‰, 2.2‰ to 1‰ and 0.8‰ to 0.1‰ in southern sector, central sector, outer channel and northern sector respectively. The pre and post monsoon period average value of salinity was found to be 15.31‰ and 3.01‰ respectively.

Alkalinity: Alkalinity of different stations in Chilika Lake was measured during pre and post monsoon period. The pre monsoon period alkalinity image (Figure 5e) shows maximum to minimum variation of alkalinity 104.92 mg/L to 46.36 mg/L, 117.2 mg/L to 58 mg/L, 109 mg/L to 36 mg/L, and 94.98 mg/L to 72.33 mg/L in northern sector, southern sector, central sector and outer channel respectively. The pre monsoon period average alkalinity of the lake was 83.60 mg/L. In post monsoon period alkalinity image (Figure 6e) shows maximum to minimum variation of alkalinity in the range from 72.66 mg/L to 42.01 mg/L, 92.5 mg/L to 68.09 mg/L, 102.3 mg/L to 43.9 mg/L and 74.6 mg/L to 45.1 mg/L in northern sector, southern sector, central sector and outer channel respectively. The post monsoon period average amount of alkalinity was found to be 67.96 mg/L.

Turbidity: In this study, turbidity was measured through turbidity meter (Model no-2100P) from different stations in the unit of Nephelometric Turbidity Unit (NTU). The turbidity ranges in pre monsoon period varies from 1.59 to 211 and in post monsoon period from 531 to 2.1 NTU. The pre monsoon period turbidity image (Figure 5f) shows high to low concentration variation of turbidity in the range from 211 to 23.9, 39.3 to 1.59, 34.2 to 3.77 and 34.1 to 17.2 in northern sector, southern sector, central sector and outer channel respectively. The pre monsoon period average value of turbidity was found to be 29.26 NTU. The post monsoon period turbidity image (Figure 6f) shows maximum to minimum concentration of turbidity ranging from 531 to 7.2, 39.5 to 2.1, 198 to 2.2 and 58.3 to 21.1 in northern sector, southern sector, central sector and outer channel respectively. The post monsoon period average value of turbidity was found to be 66.81 NTU.

Total Suspended Solid(TSS): TSS concentration in the lake shows significant spatial variability during pre and post monsoon period. The total suspended solid (TSS) was collected by filtering of each sample with the help of suction through 0.45µm mixed cellulose ester membrane (Millipore) filter paper followed by drying the filters at 80˚C in oven. The total suspended solid was expressed as the difference between the final and initial weight of the filter paper in the unit of mg/L. In the pre monsoon period TSS image (Figure 5g) shows high to low concentration of total suspended solid variation ranging from 106.2 mg/L to 8.42 mg/L, 45.6 mg/L to7.80 mg/L, 52.32 mg/L to 6.95 mg/L and 86.3 mg/L to 6.63 in northern sector, southern sector, central sector and outer channel respectively. Similarly, the post monsoon period TSS image (Figure 6g) shows maximum to minimum concentration of total suspended solid variation ranging from 273 mg/L to 12 mg/L, 26.4 mg/L to 10 mg/L, 55.2 mg/L to 10 mg/L and 59.4 mg/L to 20 mg/L in northern sector, southern sector, central sector and outer channel respectively. The pre and post monsoon period average value of total suspended solid was found to be 28.45 mg/L and 35.66 mg/L respectively.

Surface Water Temperature (SWT): Temperature plays a significant role for the photosynthesis process which is very important for lake biological communities. The surface water temperature of the Chilika Lake was measured during the sample collection period with the help of digital (multi kit-340i) thermometer. In the pre monsoon season surface water temperature image (Figure 5h) shows maximum to minimum variation of temperature ranging from 34.2°C to 32.1°C, 33.7°C to 32.3°C, 35°C to 32.2°C and 34.5°C to 32.3°C in northern sector, southern sector, central sector and outer channel respectively. The pre monsoon period average surface water temperature value was found to be 34°C. Similarly, in the post monsoon season, surface water temperature image (Figure 6h) shows maximum to minimum variation of temperature in the range from 28.2°C to 26.6°C, 29.2°C to 27.3°C, 29.3°C to 25.7°C and 28.6°C to 26.4°C in northern sector, southern sector, central sector and outer channel respectively. The post monsoon period average surface water temperature value is around 28°C.

Nutrients: Nutrients are very important for development of plant and animal life. In the lake, it is essential for growth of algae and to form the complex food web supporting the entire aquatic ecosystem. Excess amount of nutrient adversely affect the lake aquatic life and the oxygen level is depleted which creates critical condition for aquatic life. In the present study concentration of nutrients like ammonia, phosphate and nitrite is analyzed using UV-visible spectrophotometer (Varian 50 Bio). Nitrite concentration of Chilika Lake water during pre-monsoon period varied from 0.0006 to 1.5401 µmol/L. In the pre monsoon period nitrite image (Figure 5i) shows maximum to minimum concentration of nitrite variation in the range from 0.2244 µmol/L to 0.0253 µmol/L, 0.2190 µmol/L to 0.0100 µmol/L, 1.5401 µmol/L to 0.0006 µmol/L and 0.0913 µmol/L to 0.0395 µmol/L in northern sector, southern sector, central sector and outer channel respectively. In the post monsoon period nitrite image (Figure 6i) shows highest to lowest amount of nitrite variation ranging from 1.0226 µmol/L to 0.0354 µmol/L, 0.1643 µmol/L to 0.0106 µmol/L, 2.2455 µmol/L to 0.0101 µmol/L and 0.1414 µmol/L to 0.0623 µmol/L was found in northern sector, southern sector, central sector and outer channel respectively. In the pre monsoon period ammonia image (Figure 5j) shows maximum to minimum variation of ammonia ranging from 0.2992 µmol/L to 0.0849 µmol/L, 0.1411 µmol/L to 0.0698 µmol/L, 0.8220 µmol/L to 0.0728 µmol/L and 0.4073 µmol/L to 0.1034 µmol/L in northern sector, southern sector, central sector and outer channel respectively. The post monsoon season ammonia image (Figure 6j) shows highest to lowest concentration of ammonia in the range from 0.9431 µmol/L to 0.0776 µmol/L, 0.1138 µmol/L to 0.0712 µmol/L, 0.4895 µmol/L to 0.1522 µmol/L and 0.1185 µmol/L to 0.0839 µmol/L in central sector, southern sector, northern sector and outer channel respectively. The pre monsoon season phosphate image (Figure 5k) shows maximum to minimum concentration of phosphate variation ranging from 5.5480 µmol/L to 0.4237 µmol/L, 2.3598 µmol/L to 0.2394 µmol/L, 3.8470 µmol/L to 0.0167 µmol/L and 1.3555 µmol/L to 0.5123 µmol/L in central sector, southern sector, northern sector and outer channel respectively. The post monsoon period phosphate image (Figure 6k) shows maximum to minimum amount of phosphate variation in the range from 7.5056 µmol/L to 0.0284 µmol/L, 0.1268 µmol/L to 0.0121 µmol/L, 1.6081µmol/L to 0.0165 µmol/L, 0.6011 µmol/L to 0.0838 µmol/L in northern sector, southern sector, central sector and outer channel respectively. The pre monsoon average value of nitrite, ammonia and phosphate were found to be 0.1099 µmol/L, 0.1448 µmol/L and 1.3372 µmol/L respectively. Similarly, the post monsoon average value of nitrite, ammonia and phosphate were found to be 0.1423 µµ, 0.1891 µmol/L and 0.5944 µmol/L respectively.

Trophic State Index (TSI): During the pre-monsoon period the TSI image (Figure 5l) shows lowest value 51.76 in southern sector and highest value of 75.56 in the northern sector. During the post monsoon period TSI image (Figure 6l) shows the values varies from minimum of 50.06 in southern sector to a maximum of 83.96 in northern sector. The TSI pattern of the lake is found to be similar for pre and post the monsoon seasons. The average TSI value of the entire lake is 63.57 and 64.21 in pre and post monsoon period, which indicates the lake water, is in eutrophic condition in terms of secchi disk transparency.

In the present study, to observe the change in trophic status of the lake over last decade, LISS-III and Landsat-8 OLI data from 2006 to 2014 (Figure 7) which are available in the NRSC, USGS web site respectively have been taken for analysis. The average post monsoon period TSI values of the lake are presented in (Figure 8). Similarly, to compare the TSI status of pre and post monsoon period of the lake, the satellite data for the period 2013 and 2014 (Figure 9) have been taken for analysis. The average TSI values of pre and post monsoon period for the year 2013 to 2014 are presented in (Figure 10). The analysis shows the lake water is always in eutrophic condition. Analysis of the TSI images of the lake shows relatively clear water in the southern sector compared to northern, central and outer channel.

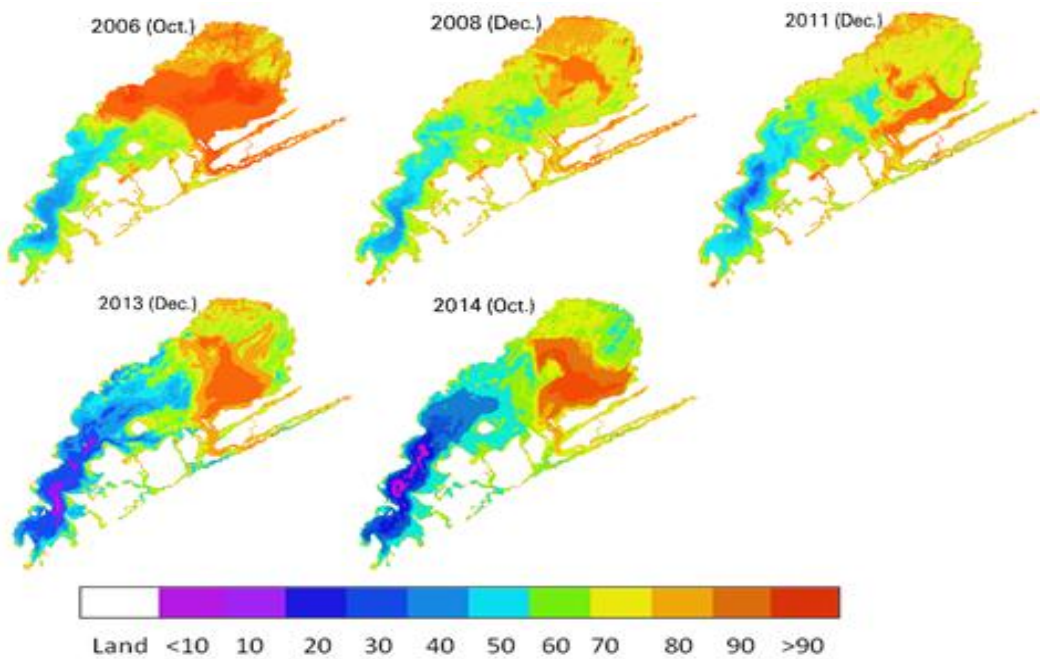

Figure 7. Trophic State Index from LISS-III and Landsat-8 OLI bands from 2006 to 2014

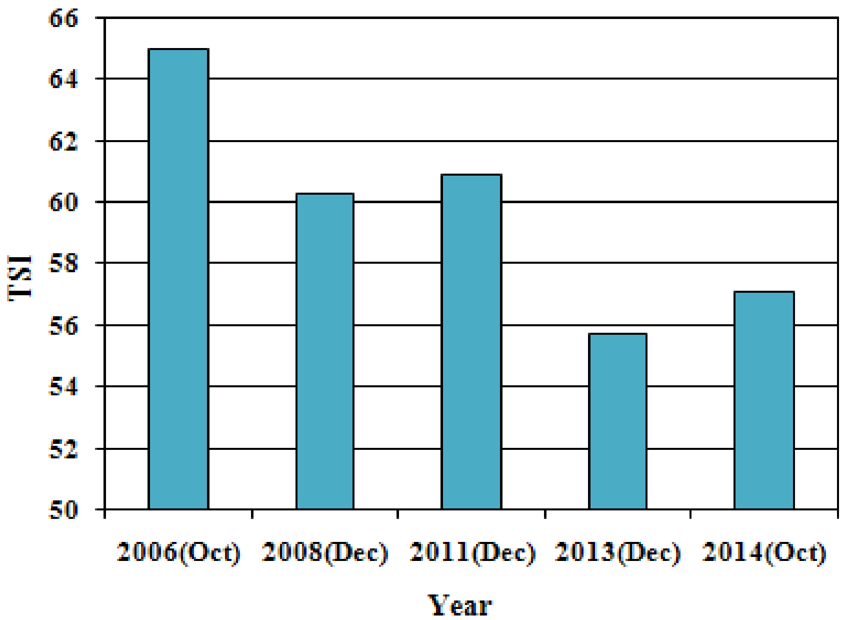

Figure 8. Comparison of average Trophic State Index (TSI) of post monsoon period of LISS-III and Landsat-8 OLI data from 2006 to 2014

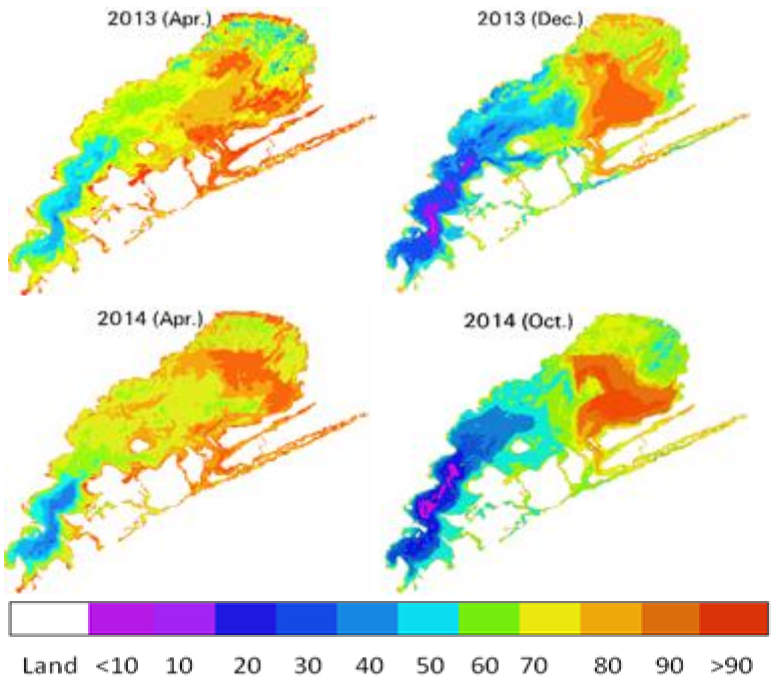

Figure 9. Trophic state index from Landsat-8 OLI bands from 2013 to 2014

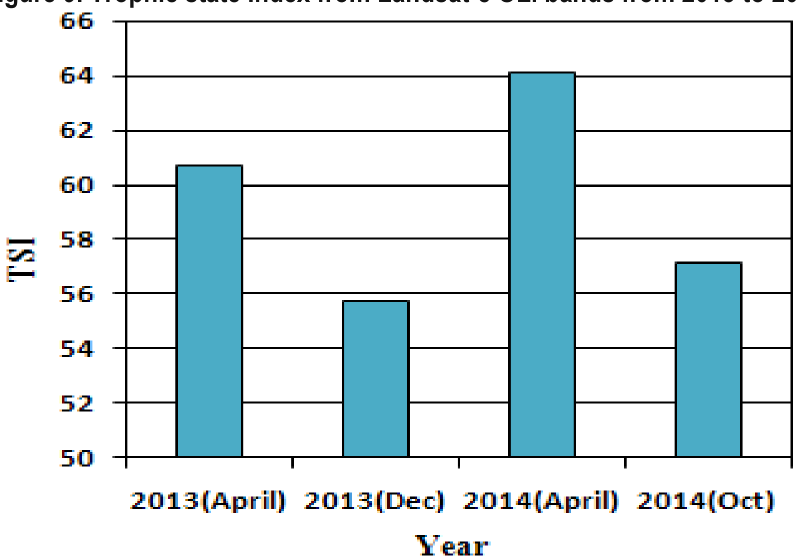

Figure 10. Comparison of average Trophic State Index (TSI) of pre and post monsoon period from Landsat-8 OLI data from 2013 to 2014

The increasing pollution level, nutrient richness in water and increasing phytoplankton population leads to lake eutrophic condition. Many researchers have used Landsat-TM (Ke-Sheng *et al*., 1998; Cheng *et al*., 2001; Olmanson *et al*., 2001, 2002; Zhang *et al*., 2003), Landsat-ETM (Nelson *et al.,* 2003; Allan *et al*., 2007; Mishra *et al*., 2011), MODIS (Min *et al*., 2008) and LISS -III (Sheela *et al*., 2010) data for study of water quality and eutrophication of the lake. In the present study water quality parameters obtained from *in-situ* measurements and satellite observations are analysed. The analysis is confined to the study of near decadal changes from the year 2006 to 2014 using satellite data. The change in trophic state index of pre and post monsoonal season in Chilika Lake is studied from the satellite data for the year 2013 and 2014. The secchi disk transparency image (Figure 5a) and (Figure 6a) shows clear water in southern sector followed by central sector. This may be attributed to mainly two reasons *i.e.* (1) the southern sector is relatively deeper, (2) the influx of river water is minimum in the southern sector compared to outer channel and northern sector which receives maximum amount of sediment from the river drainage system and sewage from urban locality. The analysis of secchi disk transparency shows the lake water is in eutrophic condition as similar to the previous study (Ganguly *et al*., 2015). The satellite derived TSI and in-situ observed TSI shows the lake water is in eutrophic condition. The high amount of DO is found in northern sector of lake compared to other sectors. This high concentration of DO may be attributed to photosynthetic process caused by the presence of aquatic weeds and influx of fresh river water (Nayak *et al*., 2004). In pre monsoon season minimum concentration of DO found in outer channel. This may be due to less solubility of oxygen in salt saturated water that depends on water temperature, water movement and salinity (Mahapatro *et al*., 2001). The minimum amount of DO also found in Balugaon area because of anthropogenic (sewage) activities. The pH image (Figure 5c) and (Figure 6c) shows entire lake water is in alkaline condition. Central sector of the lake is more alkaline than the northern sector. The high concentration of pH is related with large amount of submerged weeds present in the water. The photosynthesis activities of weeds may cause the lake water slightly higher alkaline due to intake of carbon dioxide (CO_2) from water. The low concentration of pH value found in northern sector due to decay of weeds and formation of humic acids (Nayak *et al*., 2004; Panda *et al*., 1989; Subarao *et al*., 1981). The pre monsoon season salinity image (Figure 5d) shows the outer channel, central sector and southern sector becomes highly saline. The high salinity observed in the stations of outer channel is attributed due to the well interaction of seawater through the new sea mouth. The low salinity observed in northern sector is attributed to influx of fresh river water. The post monsoon salinity image (Figure 6d) shows the southern sector becomes high saline followed by central sector and outer channel due to lesser influence of river water. The turbidity image (Figure 5f) and (Figure 6f) shows high values of turbidity in both pre and post monsoon seasons in northern sector compared to other sectors. This may be attributed to sediment-loaded influx of river water in the northern sector. The minimum concentration of turbidity is found in relatively deeper southern sector due to lesser influence of river. The TSS image (Figure 5g) and (Figure 6g) of pre and post monsoon season of the lake shows northern sector receives maximum suspended solid particles than the other sector due to high influx of river water and siltation. The pre and post-monsoonal season surface water temperature image (Figure 5h) and (Figure 6h) shows high temperature in central and southern sector compared to other sectors. The pre monsoon period surface water temperature is more than the post monsoon period. The trend of variation of surface water temperature in different sectors almost followed the atmospheric temperature (Bramha *et al.,* 2008). Some previous analysis carried out in Chilika Lake indicates mixed nature of water column with very low vertical stratification (Mahapatro *et al*., 2013). The pre monsoon season nitrite image (Figure 5i) shows high concentration of nitrite in central sector of Balugaon area due to anthropogenic (discharge of sewage and industrial pollution) activities compared to other sectors. In the post monsoon season nitrite image (Figure 6i) shows maximum amount of nitrite in northern sector near the Kalupada Ghat area due to anthropogenic activities. The pre monsoon season ammonia image (Figure 5j) shows maximum concentration of ammonia in northern sector near the Kalupada Ghat area. The post monsoon season ammonia image (Figure 6j) shows high amount of ammonia in central sector near the Balugaon area followed by low concentration of ammonia near the outer channel. The higher amount of ammonia in central may be attributed to anthropogenic activities. The post monsoon season concentration of ammonia found to be higher compared to the pre monsoon season. The pre monsoon season phosphate image (Figure 5k) shows high amount of phosphate in central and northern sector as compared to other sectors. Similarly, the post monsoon season phosphate image (Figure 6k) shows high amount of phosphate in northern sector as compared to other sectors. Ketchun (1967) observed that 2.55 µmol/L of phosphate is the highest limit of its concentration above and around which the lake water will be highly eutrophic in nature and bring health hazard for many living organisms of the ecosystem. In the present study analysis of pre and post monsoonal season data shows high phosphate in northern sector, which is beyond the pollution, limit for aquatic lives. This may be due to the release of phosphate from bottom sediment, land drainage from agricultural field, sewage discharge into the lake water. Similarly, the previous study made by Patra *et al*., 2010 shows that the DO, pH, salinity, temperature and nutrients fluctuates from one sector to another. In 2015 (Ganguly *et al*., 2015) shows the mean annual TSI (SD) is 63.7 and the water condition is alkaline throughout the lake. The present study and the previous study made by Patra *et al*., (2010), Ganguly *et al*., (2015) are found to be very similar in respect to the variation of different parameters and it is common observation that the post monsoon flood waters bring change in the lake hydrological conditions. Therefore, it is necessary to monitor trophic state index of the lake regularly, which is one of the best indicator to monitor the lake health status.

CONCLUSION

The trophic state index derived from LISS-III and Landsat 8 OLI satellite data shows that the lake is in eutrophic condition over the last decade. The in-situ observation from Secchi disk measurement indicates lake water is in eutrophic condition. The present study shows the inter-sectoral and spatio-temporal changes in the trophic state index and different physiochemical parameters of the Chilika Lake. These variations are mainly controlled by river runoff associated with south-west monsoon, turbidity and pollution. Trophic State Index is a very simple, important and effective scientific method for monitoring Lake Ecosystem. Comparison of different interpolation techniques for generation of water quality maps from field data (points observations) shows the Krigging interpolation technique provide better result. Extensive monitoring programs should be continued to create a rich database to understand the complex physical, chemical and biological processes of Chilika Lake. Monitoring process should focus on the amount of siltation in the channel and lake outlet that allow interchange of sea water in to the lake for maintenance of the biodiversity, fisheries and reduction in area of aquatic weeds. Regular time series analysis of satellite data along with observation of in-situ water quality data and its analysis will be helpful for monitoring the lake hydrological environment effectively. Further research is required to quantify the importance of different process that will be useful to protect the Chilika Lake from rapid eutrophication incidences.

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