Two Decadal Trends of Surface Chlorophyll-A Concentrations in Tropical Lagoon Environments in Sri Lanka Using Satellite and In-Situ Data

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Abstract

Two decadal trends of chlorophyll-a concentration (Chl-a) in Negombo estuary, Sri Lanka, were analyzed with satellite optical sensor data observed from 1987 to 2011 and in-situ measurements. Landsat band ratios were first regressively analyzed with in-situ Chl-a data, and the regression equation obtained was used for generation of 30 m-resolution Chl-a distribution maps using time-series Landsat images which had been atmospherically corrected. This Landsat-based regression equation was also used to correct MODIS Ocean Color 3 (OC3) Chl-a products with an overestimation error for a tropical region, and the corrected MODIS OC3 values were then regressively analyzed with ASTER band ratios on a day-by-day basis for each ASTER observation date due to unavailability of in-situ measurements at ASTER observation dates. These regression equations based on ASTER/MODIS-OC3 were then used for generation of 15 m-resolution Chl-a distribution maps using time series ASTER and MODIS-OC3 images. The above equations obtained from the Negombo estuary were also applied to Chilaw lagoon near Negombo estuary for evaluation of this approach. The results indicated that channel segments and some other parts of the Negombo estuary increased eutrophication during 1987-2011, particularly during 2000-2011, with consistency between Landsat-based and ASTER-based estimates. As a conclusion, it is mentioned that our methodology can be effectively used for prediction and mitigation of localized environmental problems including sudden fish kills frequently occurred in Negombo estuary, as a cost-effective tool complementing regular monitoring programs.

Key words: chlorophyll-a, Sri Lanka, Negombo estuary, ASTER, Landsat.

1. Introduction

Chlorophyll-a (Chl-a) has long been applied as a trophic condition index of water bodies. Although Chl-a is measured relatively easily in comparison to algal biomass, its monitoring through in-situ sampling is costly and time-consuming. Continuous sampling is a tremendous barrier in water quality monitoring over long periods of time. Satellite observation of ocean color offers several advantages over traditional monitoring techniques for coastal water bodies. The high altitude allows us to monitor a large area simultaneously and provides an instantaneous record of regional features, the area coverage renders the procedure cost-effective in comparison to conventional monitoring programs, and it can be applied to areas that may be inaccessible to investigators (Pattiaratchi *et al*. 1994) and also allows us to study past trends even when in-situ data are not available (Dahdouh-Guebas 2002). Remotely-sensed Chl-a data from satellite sensors are useful in examining the trends in the coastal environment without in-situ sampling. Because Chl-a data in coastal regions serve as an indicator of the ambient ocean optical environment, identification of trends in this remotely-sensed variable can be potentially linked to terrestrial and human interactions in the estuarine watershed (Strange *et al*. 1998). Most Chl-a retrieval algorithms using remote sensing data are for Case 1 oceanic

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waters (i.e. waters whose color characteristics are dominated by chlorophyll and have little suspended sediments or dissolved color substances). Most estuarine and coastal waters are Case 2 waters, where sediments and dissolved substances also contribute to the color and interface with the spectral signal of chlorophyll in the water. Few studies have been undertaken in the application of these data to coastal waters and more difficult challenge, however, has been developing bio-optical algorithms suitable for use in optically complex “Case 2” waters, like the tropical lagoons, where dissolved and particulate, marine and terrigenous substances affect ocean color (Pattiaratchi *et al*. 1994, Dall’Olmo *et al*. 2005, Tzortziou *et al*. 2007).

The present study focuses on the west coast of Sri Lanka, which is an area of considerable economic development, with increasing population and investment opportunities resulting in a pressure on estuarine environments. It is only recently that the biological functioning of these ecosystems has been studied in relation to anthropogenic threats (Samarakoon and van Zon 1991, CCD 2005). Research on remote sensing applications on coastal water bodies especially on water quality monitoring is sparse in Sri Lanka.

In the present study, we analyze the time series dynamics of remotely-sensed surface chlorophyll concentrations in the Negombo estuary using multispectral satellite data observed by the Landsat Thematic Mapper (TM), the Landsat Enhanced Thematic Mapper (ETM+) and the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) onboard the NASA’s Terra satellite. Landsat TM and ETM+ have four spectral bands in the visible and near-infrared (VNIR) with a spatial resolution of 30 m including the blue band, and the ASTER instrument has three spectral bands in the VNIR with a spatial resolution of 15 m (Table 1). Though Landsat and ASTER are not designed for ocean color observations, the higher spatial resolution has advantages for studying small coastal aquatic areas such as lagoons and estuaries for the determination of minor changes. The Ocean Color 3 (OC3) Chl-a products of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA’s Terra and Aqua satellites were also used for establishing Landsat-based and ASTER-based Chl-a estimation equations in the study, where OC3 is the NASA standard chlorophyll algorithm for MODIS which incorporates 443 nm, 488 nm, and 547 nm bands (O’Reilly *et al*. 2000). As the results, the Landsat-based and the ASTER-based Chl-a maps available for two decadal trend analysis of Chl-a in the Negombo are obtained, and the relationship between Chl-a changes and localized environmental problems such as sudden fish kills frequently occurred in the estuary is discussed. This study is an attempt to examine significant trends in estuarine waters influenced by changes of Chl-a distribution especially on tropical coastal regions using remote sensing.

1.1. Negombo Estuary as the Study Site

The Negombo estuary ($7^{o}6'$ – $7^{o}12'$ N; $79^{o}40'$ – $79^{o}53'$ E) is a shallow basin estuary in the Western coastal region of Sri Lanka (Figure 1a). The surface area of the estuary is around 35 km^2 and approximately 10 km in length, 3.5 km in width

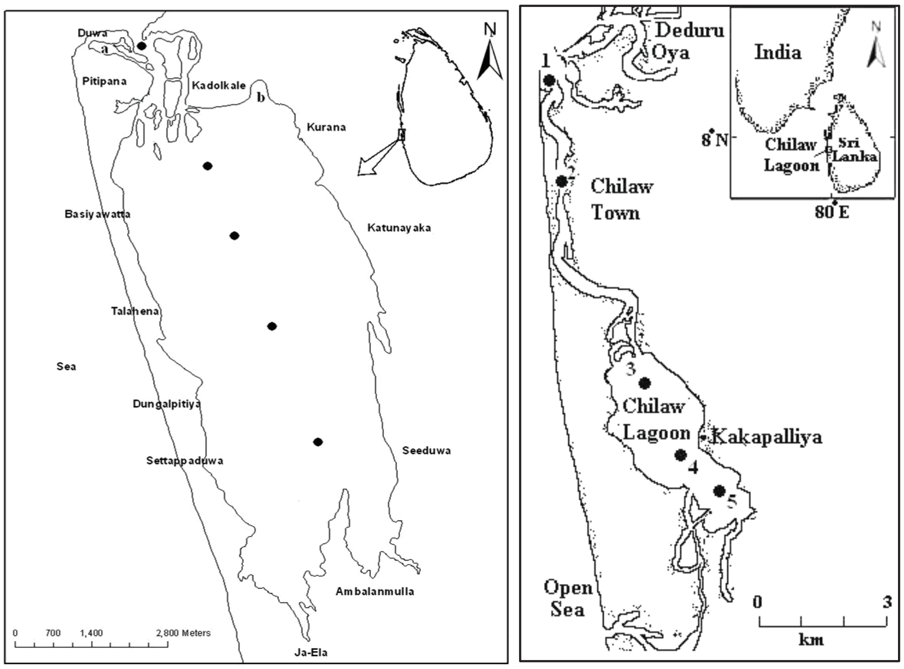

Figure 1(*a*) Figure 1(*b*)

Figure 1. (a) Map of the Negombo Estuary indicating in-situ Chl-a sampling locations; a – Kuda Ela area; b - Madabokka area, (b) Map of Chilaw lagoon with in-situ Chl-a sampling locations.

Table 1. Spectral comparisons and some specifications of Landsat and ASTER VNIR bands.

	Landsat 5 (TM)	Landsat 7 (ETM+)	ASTER
Blue band	Band 1: 0.45-0.52 µm	Band 1: 0.45-0.515µm	No blue band
Green band	Band 2: 0.52-0.60 µm	Band 2: 0.525-0.605µm	Band 1: 0.52-060 µm
Red band	Band 3: 0.63-0.69 µm	Band 3: 0.63-0.69µm	Band 2: 0.63-0.69 µm
Near-infrared band	Band 4: 0.76-0.90 µm	Band 4: 0.75-0.90 µm	Band 3: 0.76-0.86 µm
Spatial resolution	30 m	30 m	15 m
Swath width	185 km	185 km	60 km

at its widest point and has a mean depth of about 1.2 m. Fishery of this estuary is highly productive and is of great significance for the local people (Samarakoon and van Zon 1991).

1.2. Chilaw Lagoon as a Validation Site

Chilaw Lagoon is an intermittently closed small tidal lagoon (Figure 1b) on the west coast of Sri Lanka. The lagoon is 4 km long and the average width is 1.6 km. It is a shallow lagoon with an average depth of 1.1 m from Mean Sea Level (MSL). It is connected to the open ocean through two narrow and long restricting channels, located at the northern and southern ends. The northern channel is 8 km long with an average width of 80 m and a mean depth of 1.5 m. The southern channel is 5.5 km long with an average width of 20 m and an average depth of 1 m. The southern entrance is mostly closed due to sandbar formation. The topography at the northern entrance varies frequently due to formation and movement of a sandbar. The northern entrance is also closed intermittently particularly during the dry season when the river discharge is low (Baranasuriya 2001).

2. Methodology

2.1. Data Used

Monthly Chl-a data from January to December 2001 were used as in-situ measurements. Locations of in-situ measurements are indicated in Figure 1a and samples were collected using an outboard engine boat and locations were determined using a handheld Global Positioning System (GPS) receiver. Water samples to detect the Chl-a content were taken in triplicate from randomly selected sites and Chl-a were determined in laboratory using a spectrophotometer as described by Richards and Thompson (1952). Landsat Thematic Mapper (TM) (19th February 1987, 10th February 1992, 13th March 1992), Landsat Enhanced Thematic Mapper (ETM+) (15th December 2000, 14th March 2001, 28th February 2005, 23rd January 2006 and 04th December 2006) and ASTER (28th October 2000, 12th February 2005, 18th February 2007, 17th November 2007, 03rd December 2007, 08th March 2008, 30th December 2008, 31st January 2009, 16th February 2009 and 24th December 2009) satellite images were selected as remote sensing data sources.

2.2. Landsat Data Analysis with In-situ Measurements

In-situ Chl-a data on the same date were regressively analyzed with Landsat band ratios of cloud free Landsat imagery on 14th March 2001. Finally, the regression equation of the Landsat band ratio with highest correlation was used for the generation of 30m resolution Chl-a distribution maps using atmospherically-corrected time-series Landsat images.

The dark object subtraction (DOS) method was used as an atmospheric correction technique to correct all the Landsat images. DOS is perhaps the simplest, yet most widely used image-based absolute atmospheric correction approach (Lathrop *et al*. 1991, Lavery *et al*. 1993, Ekstrand 1994, Huguenin *et al*. 1997). This approach assumes that the radiance received by the sensor in the wavelength band λ, $L_T(\lambda)$, is given by

$$L_T(\lambda) = L_A(\lambda) + L_W(\lambda) \quad (1)$$

where $L_A(\lambda)$ is the path radiance due to additive scattering effects and $L_W(\lambda)$ is the water leaving radiance. This method assumes that $L_A(\lambda)$ remains constant for the whole image and a dark pixel is determined within the image where it is assumed that the incoming radiation to the surface is perfectly absorbed by the water column and therefore the radiance recorded by the satellite is due to $L_A(\lambda)$ alone. The digital band value recorded by the satellite for the dark-pixel in each band is subtracted from the whole image of that band, thus removing atmospheric additive effects. In this study, pixels in open ocean (~30 km offshore) with very low productivity (Pattiaratchi *et al*. 1990) were selected for determination of dark pixel characteristics (assumed to be pixels with chlorophyll concentrations < 0.3 μg^{-1}).

For studying long term changes of Chl-a, Landsat images representing only North-East monsoonal period of Sri Lanka (December to March) were selected in order to minimize the seasonal effects because monsoon rains can affect the distribution pattern of Chl-a especially in shallow coastal areas (Yapa 2000). Due to the failure of Scan Line Corrector (SLC) of Landsat on 31st March 2003 (USGS 2010), all the Landsat images after 2003 were interpolated with spectral data across the gaps in SLC-off imagery, and missing and bad values were replaced. Those corrected images were used to develop Chl-a distribution maps after 2003. This approach assumes that the multiplicative component (transmittance, gain calibration coefficient, sun zenith angle etc.) is same among all the Landsat data.

Incidentally, Chl-a estimation by the regression equation between the Landsat band ratio and in-situ measurements, employed here, is a traditional approach, but the coefficients have been adjusted for the Negombo estuary located in a tropical region.

2.3. MODIS Chl-a Correction and ASTER Data Analysis

The original MODIS Chl-a product based on the OC3 algorithm should be corrected because it may give overestimated values in tropical coastal waters (Brando *et al*. 2006). The original MODIS Chl-a and the Landsat Chl-a derived in the previous section were therefore compared using a linear regression to determine a MODIS Chl-a correction equation. Next, three ASTER VNIR band ratios such as B1/B2 were compared using a linear regression with the corrected MODIS Chl-a obtained for each ASTER date on a day by day basis. Finally, the regression equation of the ASTER band ratio with highest correlation (described later) was used to generate high-resolution Chl-a distribution in Negombo estuary using ASTER images combined with the corrected MODIS Ch-a. This approach that combines ASTER band ratio and the corrected MODIS OC3 values is a new proposal by the present paper. In this approach, atmospheric correction will not be needed for ASTER data, because the regression equation for each ASTER date is established for atmospherically-corrected OC3 Chl-a values on a day by day basis.

2.4. Validation Using Chilaw Lagoon

The Landsat-based and the ASTER-based Chl-a estimation equations obtained from the Negombo estuary were validated using the in-situ Chl-a data measured from January to August 2001 in Chilaw lagoon. Water samples for Chl-a determination were taken from 5 sites in triplicate to cover the entire lagoon (Figure 1b), and then Chl-a data were determined in the laboratory using a spectrophotometer as described by Richards and Thompson (1952). Landsat Thematic Mapper (TM) (19th February 1987), Landsat Enhanced Thematic Mapper (ETM+) (15th December 2000 and 09th December 2006), ASTER (12th February 2005, 03rd December 2007, 08th March 2008, 13th February 2011, 02nd April 2011) satellite images were selected as remote sensing data sources. The DOS method was used as an atmospheric correction

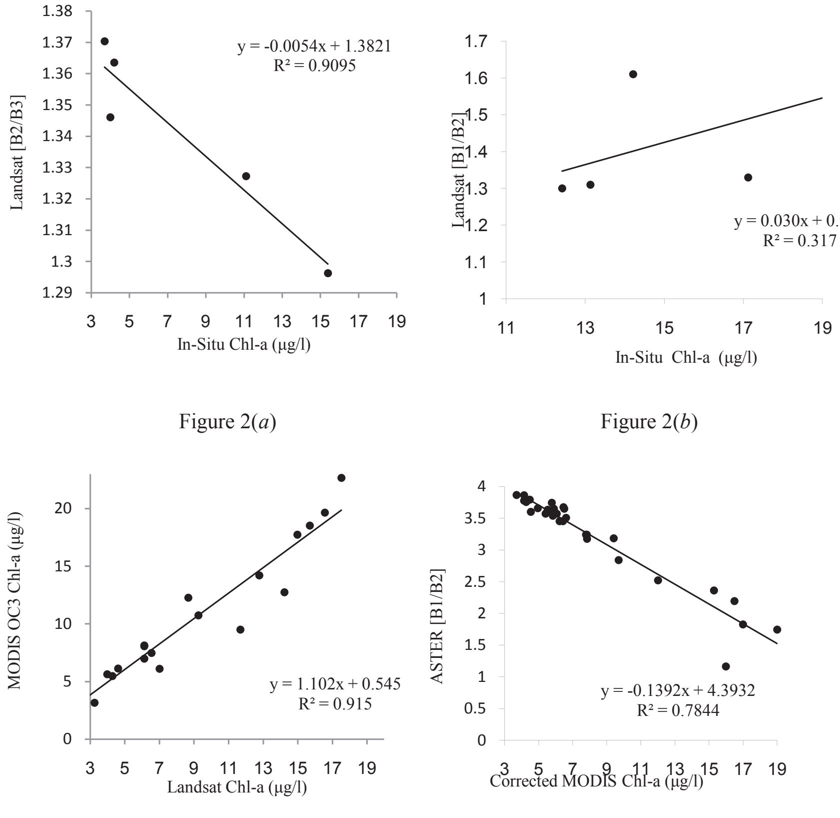

Figure 2(*a*) Figure 2(*b*)

Figure 2(*c*) Figure 2(*d*)

Figure 2. (a) Correlation between the in-situ Chl-a and the Landsat [B2/B3] (b) Correlation between the in-situ Chl-a and the Landsat [B1/B2] (c) Correlation between the Landsat Chl-a and the MODIS OC3 Chl-a (d) Correlation between the corrected MODIS OC3 Chl-a and the ASTER [B1/B2].

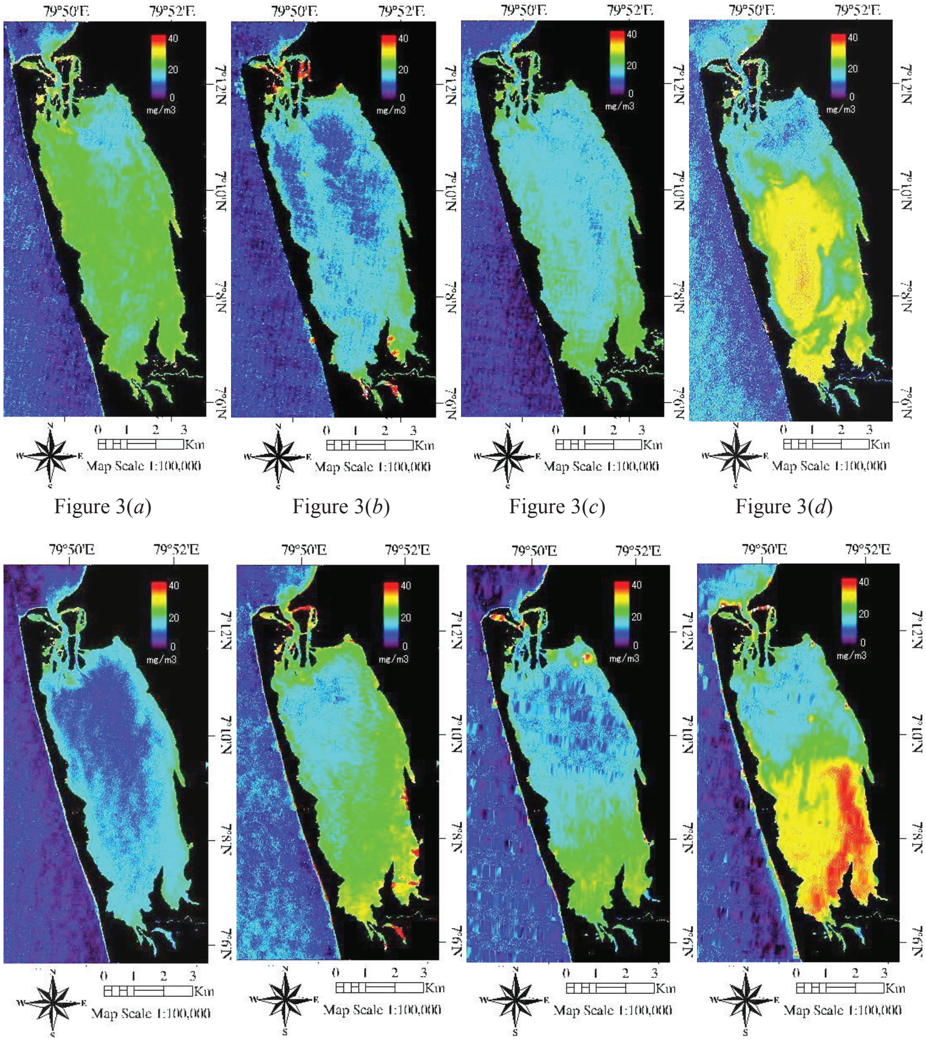

Figure 3(*a*) Figure 3(*b*) Figure 3(*c*) Figure 3(*d*)

Figure 3(*e*) Figure 3(*f*) Figure 3(*g*) Figure 3(*h*)

Figure 3. Chl-a distribution maps of Negombo estuary derived from Landsat TM and ETM+ band 2/3 ratio. (a) 19 February 1987, (b) 10 February 1992, (c) 13 March 1992, (d) 15 December 2000, (e) 14 March 2001, (f) 28 February 2005, (g) 23 January 2006, (h) 09 December 2006.

technique to correct all Landsat images (Ekstrand 1994, Huguenin *et al*. 1997). As for the Landsat-based estimation, the band ratio of B2/B3 atmospherically corrected was applied to the same regression equation with the Negombo estuary to generate 30 m resolution Chl-a distribution maps. As for the ASTER-based estimation, the band ratio of B1/B2 not corrected for atmospheric effects was applied to the same regression equation with the Negombo estuary to generate 15 m resolution Chl-a distribution maps, where this estimation needs the assumption that atmospheric conditions were same between Negombo estuary and Chilaw lagoon on each ASTER date, and we can assume it because they are located closest proximity. Thus, time series changes of Chl-a concentrations, especially on in-situ sampling locations, were monitored using high resolution Chl-a distribution maps derived from Landsat and ASTER. The in-situ data measured in the Chilaw lagoon were then compared with the Landsat-based and the ASTER-based Chl-a values for validation of the Chl-a estimation equations.

3. Results

The results for the Landsat TM data show that bands 2 and 3 are useful wavelengths for estimating Chl-a concentrations as ASTER bands 1 and 2 (Sakuno *et al*. 1999). A strong relationship was found between Landsat [B2/B3] ratio and Chl-a on 14th March 2001 (R^2=0.91, Figure 2a) when compare to Landsat [B1/B2] (R^2=0.32, Figure 2b). Therefore Landsat [B2/B3] ratio was used to generate Landsat-based Chl-a maps. Figure 2c displays the plot of the derived Landsat Chl-a and the MODIS OC3 Chl-a for the same date. This relationship was used to derive the correction equation for MODIS OC3 Chl-a. Figure 2d shows the plot for corrected MODIS OC3 Chl-a and the ASTER [B1/B2]; as such this ratio was used to generate ASTER-based Chl-a maps. Similar relationship was successfully introduced by

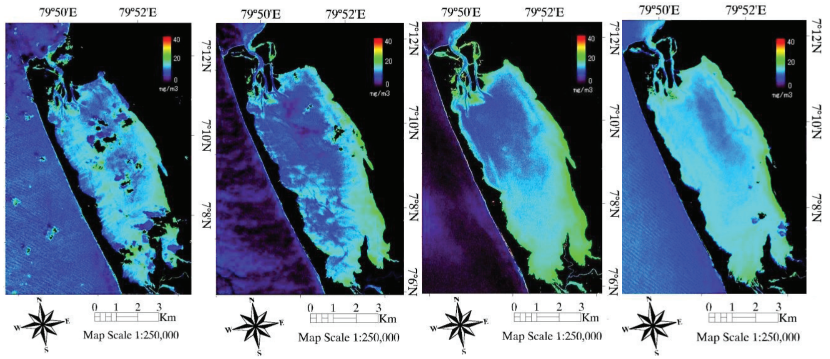

Figure 4(*a*) Figure 4(*b*) Figure 4(*c*) Figure 4(*d*)

Figure 4. Chl-a distribution maps derived from ASTER band 1/2 ratio. (a) 28 October 2000, (b) 18 February 2007, (c) 16 February 2009, (d) 20 May 2011.

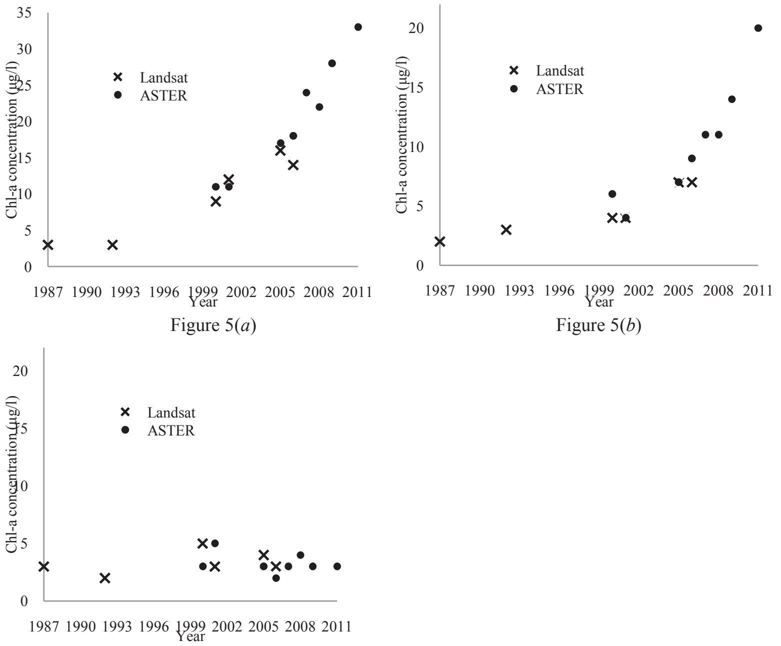

Figure 5(*a*) Figure 5(*b*) Figure 5(*c*)

Figure 5. Changes of Chl-a during study period at selected locations at Negombo estuary. (a) Kuda Ela area, (b) Mada bokka area, (c) estuary middle as a reference point.

(Dahanayaka *et al*. 2010) to the Puttalam lagoon, Sri Lanka to develop high resolution Chl-a maps. Figure 3 shows examples of 30m resolution Chl-a distribution maps estimated from Landsat band 2/3 ratio using the regression equation between the in-situ Chl-a and the Landsat band 2/3 ratio. Figure 4 shows examples of 15m resolution Chl-a distribution maps estimated from ASTER band 1/2 ratio using the regression equation between the corrected MODIS OC3 Chl-a and the ASTER band 1/2 ratio. Results indicate that there are almost no eutrophic conditions in overall throughout the study period and also shows considerable spatial heterogeneity with higher concentrations being recorded water stagnant areas in channel segment and in water adjacent to freshwater outlets. However, localized eutrophication is shown at the head region of the estuary especially close to Kuda Ela and Madabokka area (Figure 1a). Changes of Chl-a contents in Kuda Ela, Madabokka and middle region of estuary (as a reference point) during the study period are shown in Figure 5(a), 5(b) and 5(c) respectively. Sudden increase of Chl-a in both areas could be observed in 2000-2011 period.

Figures 6a and 6b show examples of 30 m resolution Chl-a distribution maps using Landsat TM and ETM+ satellite images respectively in Chilaw lagoon as a validation site. ASTER based Chl-a distribution maps with 15 m resolution are also shown in Figures 6c and 6d. Figure 7 indicates the remotely-sensed Chl-a changes during the study period with compared to in-situ data in different sampling locations. According to the results, changes of Chl-a content during the 1987-2000 period cannot fully be explained due to lack of satellite data. However, it is surely demonstrated that there was a significant increase of Chl-a content in 2000-2005 and after that more or less constant values were observed.

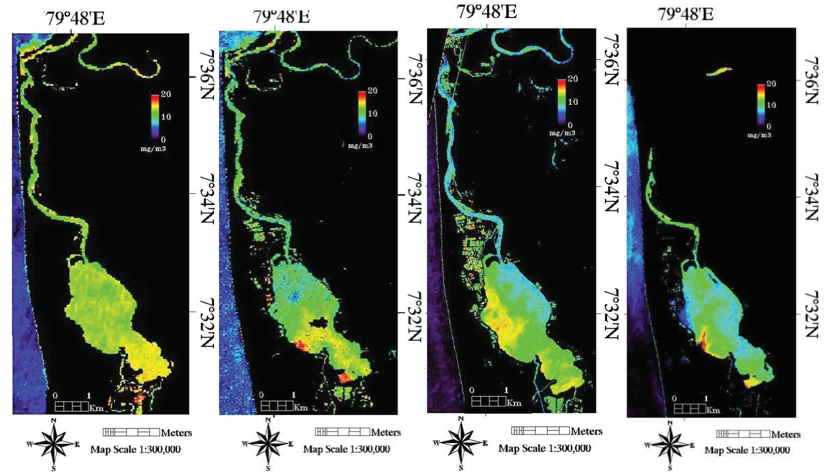

Figure 6(*a*) Figure 6(*b*) Figure 6(*c*) Figure 6(*d*)

Figure 6. Chl-a distribution maps of Chilaw lagoon derived from Landsat TM data (a) 19 February 1987, Landsat ETM+ data (b) 15 December 2000 and ASTER data (c) 03 December 2007, (d) 13 February 2011.

Furthermore, it is also observed that in-situ Chl-a values lie within the possible trend line of satellite based Chl-a.

4. Discussion

Two satellite systems have been used predominantly to predict Chl-a in Negombo estuary. These are the Landsat TM & ETM with the in-situ data and the ASTER with the corrected OC3 products of MODIS. Results indicate that Chl-a distribution in the Negombo estuary, Sri Lanka could be estimated using Landsat band 2/3 ratio and ASTER band 1/2 ratio. Chl-a is positively correlated with the green band reflectance and negatively correlated with the red band reflectance. Therefore, the reflectance ratio of green and red bands becomes a robust parameter to estimate the Chl-a content (Kishino *et al*. 2005). There was a significant relationship between derived Landsat Chl-a and MODIS OC3 Chl-a, but the comparative values of MODIS were higher than the Landsat Chl-a values. Earlier researchers have also indicated that the OC3 algorithm may overestimate the Chl-a especially in tropical coastal waters (Brando *et al*. 2006). The newly established equations in the present study can estimate Chl-a concentrations with a correlation coefficient (R) of 0.91 for Landsat images and with that of 0.78 for ASTER images. There was a significant increase of Chl-a especially in water stagnant areas of the Negombo estuary (eg. Kuda Ela and Madabokka areas) during 1987-2011, and these areas are known as eutrophic areas. For example, sudden fish kills often observed in the Kuda Ela area are surely the result of fish suffocation caused by night-time oxygen depletion during dry periods. Domestic waste and waste from fish drying places directly enter this area resulting in high accumulation of nutrients. This is coupled with disturbance of water circulation due to narrowing of the outlet channels, and leads to high algal growth resulting in sudden fish kills (Dahanayaka *et al*. 2012). These fish kills in water stagnant areas in Negombo estuary could be predicted by high resolution Chl-a distribution maps which could be helpful to mitigate such problems. Monitoring Chl-a using Multi satellite data is useful for comparisons and validations in different resolutions and in different time periods. The present study successfully performed the examination of time series trends of spatial distribution of Chl-a. These results can be explained further by the changes of topography of the channel segment occurred during the study period. Since topography plays an important role in the discharge and the type of sediment transported, changes of topography will directly affect the estuarine productivity via Chl-a distribution (Dahanayaka *et al*. 2012).

Negombo estuary has been disturbed due to poor water exchange, illegal land reclamation, ad-hoc mangrove planting, wastewater discharge and siltation (CEA and Euroconsult 1994). Significant changes of the Chl-a concentrations in Negombo estuary should be monitored together with rainfall, current pattern and wind directions. In this regard, a statistical analysis of extensive time series data from field observations is also important. Although human actions will affect the entire ocean through long-term processes, estuaries and lagoons are sensitive indicators of human activities. Numerous studies show that anthropogenic factors affect fresh water inflow as well as the nutrient and sediment supply, which in turn affects the composition of species and ecosystem elements such as water and nutrient cycling (Gergel *et al*. 2002).

Rural inputs such as deforestation, industrial and agricultural production, and urban inputs such as sewage systems increase the nutrients content in fresh water inflow. In addition, climate change can also result in the changes in fresh water inflow patterns and nutrient loading (Jain and Lall 2001, Tang *et al*. 2005). Increases in nutrient loading can threaten the ecological balance in estuarine and lagoon waters through increased phytoplankton productivity leading to eutrophication, hypoxia (low dissolved oxygen in bottom waters), and anoxia (zero dissolved oxygen in bottom waters)

(Rabalais *et al*. 1996). Humans can affect chlorophyll concentrations in the fresh water inflow region via higher nutrient loading, particularly nitrogen and phosphorous, or by influencing the mean flow and sediment load. Increases in nutrients will commonly lead to increased phytoplankton productivity and thus an increase in remotely sensed Chl-a. In the ASTER based Chl-a maps (Figure 4), the eastern coastal area of the estuary shows high Chl-a concentrations, which proves the above phenomena due to the fresh water circulation, where the eastern side of the estuary is flow of the fresh water taken place (Arulananthan 2004). On the other hand, when we consider Chilaw lagoon, prawn farming has been a popular venture in the area, particularly along inlet channels (Corea *et al*. 1995). The total area of prawn farms has gone up by 48% from 1994 to 1998. This had resulted in severe environmental and ecological problems. The fish catch per unit effort from the lagoon has dropped by 4 - 1.5 kg from 1994 to 1997 (Dahdouh-Guebas *et al*. 2002). After 1997, the prawn farming suffered from wide spread viral diseases, such as white spot, probably because of its uncontrolled expansion. Over establishment of farms has resulted in the reduction of freshwater supply to the lagoon leading to low water exchange and hence polluting it. This has been further aggravated by pesticides, abnormally high nutrient concentrations and oxygen deficits (Corea *et al*. 1995). These effects cannot be explained using present results due to data gaps in the 1994-1997 period and afterwards until 2000. However, after 2000, the increase of Chl-a may be due to the development of prawn industry at its second stage and other anthropogenic factors. Further, the present study showed that the Chl-a estimation equations applied will be effective to monitor Chl-a at other adjacent tropical lagoons such as Chilaw lagoon.

In the present study, the Chl-a values were obtained by combination of different satellite sensors, nevertheless they have continuously changing trends, and also are consistent with the in-situ measurements. It should indicate that our approaches worked successfully, but various error factors should also be considered. First, a remotely-sensed Chl-a value for estuarine waters is generally less accurate than that for open ocean waters due to increased turbidity caused by primarily colored dissolved organic matter (CDOM) and suspended sediments (Bukata *et al*. 1991). Though we selected drier season for western coast represent North-East monsoonal period for the present analyses, we need to consider that the obtained Chl-a values surely have some variations and biases induced by turbidity. In addition, we

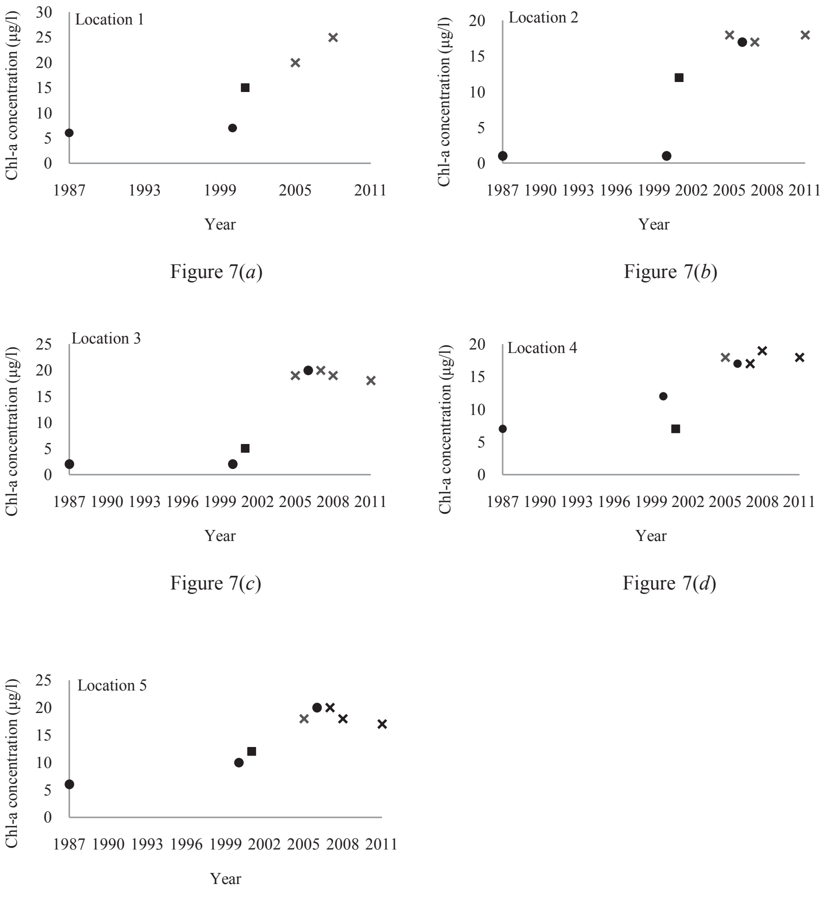

Figure 7(*a*) Figure 7(*b*)

Figure 7(*c*) Figure 7(*d*)

Figure 7(*e*)

Figure 7. Remote sensed Chl-a changes during study period with comparison with in-situ data in different sampling locations of Chilaw lagoon. (a) Location 1, (b) Location 2, (c) Location 3, (d) Location 4, (e) Location 5 (symbols: dot – Landsat based Chl-a; square – in-situ Chl-a; cross – ASTER based Chl-a)

rely on the corrected OC3 products for the ASTER-based estimation, and expect that the OC3 algorithm can remove the suspended solid effects to some extent, but this should be validated carefully in the future. In the Landsat-based estimation, we used DOS which is a simple atmospheric correction method, but DOS cannot remove multiplicative effects (atmospheric transmittance) caused by both scattering and absorption, though it can remove the additive scattering component caused by path radiance (Chavez 1996). So if needed, we will apply more accurate atmospheric correction, for example using a radiative transfer code FLAASH (Cooley *et al*. 2002).

5. Conclusion

The successful use of satellite imagery to evaluate chlorophyll trends over two decades suggests that the eutrophication in some parts of the estuary has increased during the 1987-2011 period, considerably affecting the water quality, fishery and biodiversity, concluding that remote sensing can be used to support the determination of long term changes of Chl-a of Negombo estuary and development of time series Chl-a distribution maps. High-resolution Landsat and ASTER Chl-a distribution maps derived will be useful for the determination of localized effects in tropical lagoon environments such as Negombo estuary in Sri Lanka, and such information will be useful to identify the areas with high eutrophication and remedial action could be taken well in advance in order to mitigate sudden fish kills that frequently occur in such areas. Future work with more satellite images and in-situ ground data will help to map the Chl-a distribution with a higher accuracy. Such research can be useful in monitoring the water quality and in improving the understanding of the relationship between remotely sensed Chl-a and in-situ chlorophyll measurements in optically complex estuarine waters.

Acknowledgement

The authors wish to thank Earth Remote Sensing Data Analysis Center (EARSDAC), Tokyo for supplying original ASTER data and also the Global Land Cover Facility (University of Maryland) for providing free Landsat data that were used in this study. Financial assistance provided by the Graduate School of Science and Engineering of the Ibaraki University, Japan is also acknowledged with deep gratitude.

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