Monitoring Land Use Changes and their Impacts on the Productivity of Negombo Estuary, Sri Lanka Using Time Series Satellite Data

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Abstract

The changes of land area and vegetation cover in the channel segment of the Negombo estuary, Sri Lanka from 1987 to 2009 were assessed with the multivariate alteration detection (MAD) algorithm using multi-temporal satellite images of Landsat TM, ETM+ and ASTER. Changes in chlorophyll a (Chl-a) distribution were also studied using time series Landsat satellite data. The study successfully detected changes in land area and vegetation cover during the study period. Results indicated that the channel area of the Negombo estuary had significantly reduced during the study period with rapid changes from 2000 onwards. A notable increase in land area in urbanised areas around the channel segment and an increase in the density of mangroves around some islets were also detected. New islets have also formed in the channel segment during 1987-2009. The results also indicated that during this period there was a significant increase of Chl-a content especially in water stagnant areas at Kuda Ela and Madabokka, leading to localised eutrophication. This 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.

Introduction

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh, 1989). A variety of digital change detection techniques has been developed and basically, the different algorithms can be grouped into the following categories: algebra (differencing, rationing, and regression), change vector analysis, transformation (e.g. principal component analysis, multivariate alteration detection, Chi-square transformation), classification (post-classification comparison, unsupervised change detection, expectation-maximisation algorithm) and hybrid methods (Coppin et al. 2004; Mas, 1999 and Singh, 1989).

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The multivariate alteration detection (MAD) transformation (Nielsen et al. 1998; Canty and Nielsen, 2006; Nielsen, 2007) is based on a classical statistical transformation referred to as canonical correlation analysis to enhance the change information in the different images. The MAD transformation which is a more accurate unsupervised change detection method for satellite images, can be applied on any spatial and/or spectral subset of the full data set (Nori et al. 2008), was used as the change detection technique in the present study.

Accurate chlorophyll a (Chl-a) data are critical for determining the magnitude and variability of lagoon primary production, the effect of biological processes on carbon dioxide drawdown in surface waters and for improving the understanding of phytoplankton dynamics in lagoons and estuaries (O'Reilly et al. 1998). However, measurements made on samples collected at different stations may not be the representatives of the entire region of interest. To understand lagoon productivity, it is necessary to conduct simultaneous measurements over large areas of lagoon waters. Application of remote sensing technology from space is providing biologists with the means of acquiring these synoptic data and it offers a cost-effective tool for complementing regular monitoring programmes (Pattiaratchi et al. 1994). This paper describes the results of digital change detection of the channel segment of the Negombo estuary, Sri Lanka with time series satellite data during 1987 to 2009 using the MAD technique.

Satellite data sources such as the Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM+) and the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) onboard the NASA's Terra satellite were used for the analysis. 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. The ASTER instrument has three spectral bands in the VNIR with a spatial resolution of 15 m. Fig. 1 and Table 1 show the spectral comparison of ASTER and Landsat VNIR bands. Though Landsat TM and ETM and ASTER are not designed for ocean colour observations, the higher spatial resolution has advantages for studying small coastal aquatic environments such as lagoons and estuaries to detect minor changes. The objective of the present study was to investigate the changes in the land use pattern in the channel area of the Negombo estuary, using satellite data. The trends of estuarine productivity are also determined in order to identify the possible areas prone to eutrophication so that fish kills, which had been experienced in this estuary, could be predicted and remedial action could be taken.
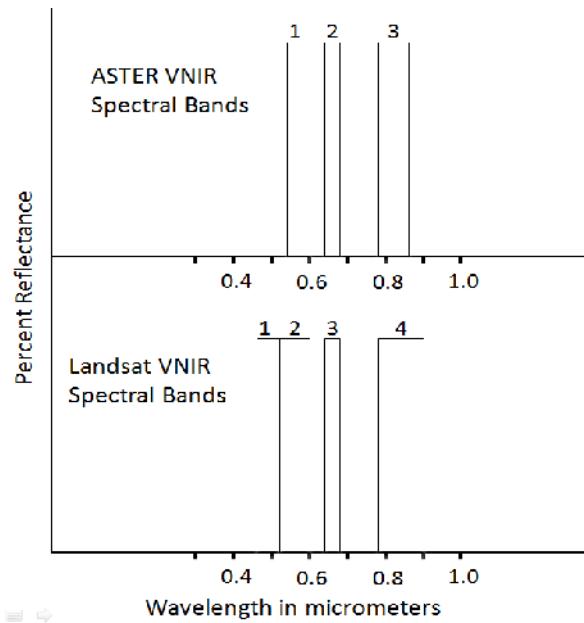
Fig .1. Spectral positions of VNIR bands of ASTER and Landsat (SIC, 2011).

Table 1. Spectral comparison and specifications of ASTER and Landsat VNIR bands.

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

Materials and Methods

Study Site

The Negombo estuary ($7^o6'$ – $7^o12'$ N; $79^o40'$ – $79^o53'$ E), which is one of the most productive estuaries in Sri Lanka, is a shallow basin estuary in the western coastal region (Fig. 2). The surface area of the estuary is around 35 km^2. The estuary is approximately 10 km in length, 3.5 km in width at its widest points and has a mean depth of about 1.2 m (Samarakoon and van Zon, 1991; CEA and Euroconsult, 1994). Around 70% of its area is less than 1.0 m in depth during low tide. Several islets are located close to the sea mouth of Negombo estuary (Fig. 3) and thus the northern part of the estuary is segmented into a number of channels. A deeper channel extends towards the middle part of the estuary, which is the estuary proper. Although there is one opening to the sea, this channel is divided into two towards the estuary proper. The estuary is characterised with a large freshwater supply and restricted water exchange with the open sea. Channel segment (Fig. 3) is very important for the continuation of estuarine functions. In the seaward side, the channel bed consists of sand, but the side facing the lagoon is muddy (CEA and Euroconsult, 1994). In the channel segment, there is a traditional fishery called stake-seine fishery which has been in existence since the 18th century. Stake-seines are operated by people in surrounding areas of the channel segment targeting shrimp that migrate from the estuary to the sea (Samarakoon and van Zon, 1991). During the last few decades, the channel segment has been disturbed due to poor water exchange, illegal land reclamation, ad-hoc mangrove planting, wastewater discharge and siltation. Further, the channel segment serves as an anchorage for several hundred fiberglass boats with outboard motors and about 300 boats with inboard engines. Since the early 1980s, haphazard expansion of piers and landing points took place altering the flow pattern and sedimentation in the channel segment. As a result, new sand shoals have been formed obstructing fishable and navigable areas. Unauthorised houses have also been built on the intertidal sand shoals in the channel segment causing serious impacts on hydrology. Functional sea grass beds have also been smothered by deposition of sediments resulting in their rapid depletion (CEA and Euroconsult, 1994).

Data used

Multitemporal satellite imageries from Landsat Thematic Mapper (TM) (19 February 1987, 10 February 1992, 13 March 1992), Landsat Enhanced Thematic Mapper (ETM+) (15 December 2000, 14 March 2001, 28 February 2005, 23 January 2006 and 04 December 2006) and Terra ASTER (28 October 2000, 12 February 2005, 3 December 2007 and 16 February 2009) were used as remote sensing data sources for change detection. A sub scene covering approximately 36 km^2 was extracted as the area of interest for change detection of the channel segment and the entire estuarine area was selected to determine the changes of Chl-a distribution. First, the results of a change detection method were described with visual interpretation, field data and Google

Earth high resolution satellite imagery data. Then high resolution Chl-a distribution maps were developed from Landsat TM and ETM+ satellite data and already published in-situ Chl-a measurements (Jayasiri and Dahanayaka, 2009). Locations of these in-situ measurements are indicated in Fig. 2.
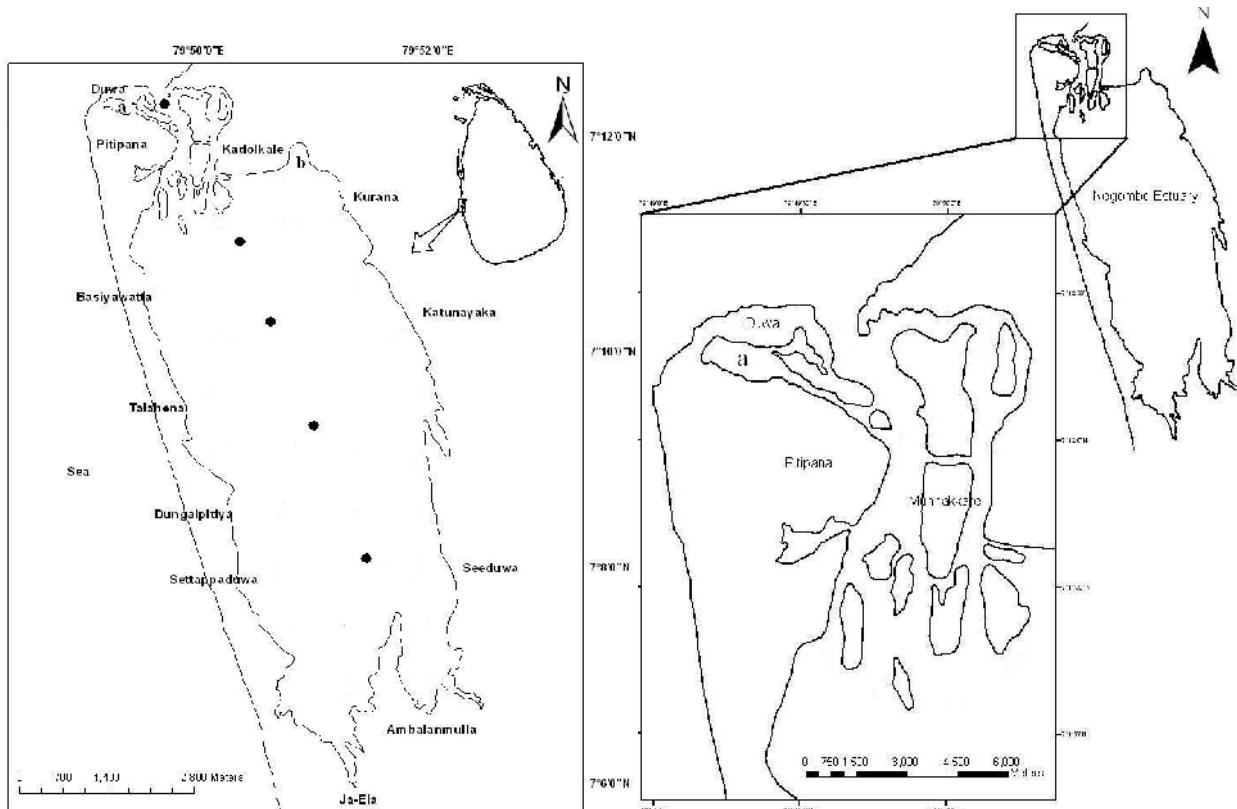
Fig. 2. Map of the Negombo Estuary indicating in-situ Chl-a sampling locations during 2001 by Jayasiri and Dahanayaka (2009); a – Kuda Ela area; b - Madabokka area

Fig. 3. Map of the channel segment, Negombo estuary; a – Kuda Ela area

Data processing for determine topographic changes

MAD technique was used to assess the changes in the land and vegetation cover in the channel segment of the estuary. The MAD transformation is based on the construction of two linear combinations of two multivariates of multispectral images and using the difference between these two linear combinations to indicate the temporal differences (Nielsen et al. 1998, Canty and Nielsen, 2006, Nielsen, 2007).

The mathematic expression of the MAD is:

$$Z = a^T X - b^T Y \qquad (1)$$

where *X* and *Y* are the two multivariates of two images, *a* and *b* are coefficient vectors of linear combinations and *Z* is the difference variable. Variance of *Z* is to be maximised subject to constraint that both $a^T X$ and $b^T Y$ have unit variances. Vectors *a* and *b* could be solved by employing the established Canonical Correlation Analysis used in Multivariate Statistics. The correlation between $a^T X$ and $b^T Y$ is called canonical correlation. The larger the variance of *Z,* the lower is the canonical correlation. Therefore, the core idea of MAD is to detect the maximum differences between two images by removing the correlations between them as much as possible.

MAD has few important merits. For example, all components of MAD variants are uncorrelated with each other implying that different categories of changes may be sorted into different resultant image components. Further, the MAD components are arranged in the decreasing order of the variances, i.e., the first component has maximum spread in its pixel intensities and ideally the maximum change information, while the last component has the minimum change information. In addition, the MAD variants are invariant to linear transformations of the original image intensities indicating that this method is insensitive to differences in atmospheric conditions or sensor calibrations at two acquisition times so that requirements on radiometric correction or normalisation could be reduced greatly. This is a significant advantage over traditional methods for change detection. The MAD transformation can be augmented by subsequent application of the maximum autocorrelation factor (MAF) transformation, in order to improve the spatial coherence of the difference components.

Landsat data were used from 1987 to 2000 and ASTER imageries were used from 2000 to 2009 because of the failure of the Scan Line corrector (SLC) of Landsat after 31 March 2003 (USGS, 2010). The images were co-registered to each other. Comparisons were made within Landsat imageries, within ASTER imageries and between Landsat imageries and ASTER imageries to avoid seasonal changes due to events such as flooding, tidal effects and sand depositions. For the geometric correction, the 1987 scene was co-registered to the 2009 scene using ground control points, which had been acquired through the Universal Transverse Mercator coordinate system (UTM) projection. Nearest neighbour re-sampling was applied when assigning pixel values to the aligned raster for the 2009 scene. A change matrix of the MAD technique was created using registered and resized imageries. MAD components were then examined to identify the quality of changes. The change detection results were validated with visual interpretation, field data and Google Earth high resolution satellite imagery data.

### *Data processing to determine Chl-a changes*

Available in-situ Chl-a data (Jayasiri and Dahanayaka, 2009) were regressed with the band ratios of the cloud free Landsat imagery on the day closest to the sampling date of Chl-a which was 14 March 2001. The regression equation with the highest correlation was used to develop algorithm for the generation of 30 m resolution Chl-a distribution maps using atmospherically corrected time series Landsat imageries. The dark object subtraction (DOS) method was used for atmospheric correction of all the Landsat imageries based on 14 March 2001 image. DOS is perhaps the simplest yet most widely applied image-based absolute atmospheric correction approach used in change detection applications (Ekstrand, 1994; Huguenin et al. 1997). This approach assumes the existence of dark objects (zero or small surface reflectance) throughout a Landsat scene and a horizontally homogeneous atmosphere. For studying changes of Chl-a content in the Negombo estuary over a long time, Landsat imageries of only the north-east monsoonal season (December to March) were used in order to minimise the seasonal effects because the monsoon rains affect the distribution pattern of Chl-a especially in shallow coastal areas (Yapa, 2000). Due to the failure of SLC of Landsat on 31 March 2003 (USGS, 2010), all the Landsat imageries after 2003 were interpolated with spectral data across the gaps in SLC-off imagery and missing bad values were replaced. Those corrected imageries were used to develop Chl-a distribution maps after 2003. Methodology and data analysis process is shown in Fig.4 as a flow chart.
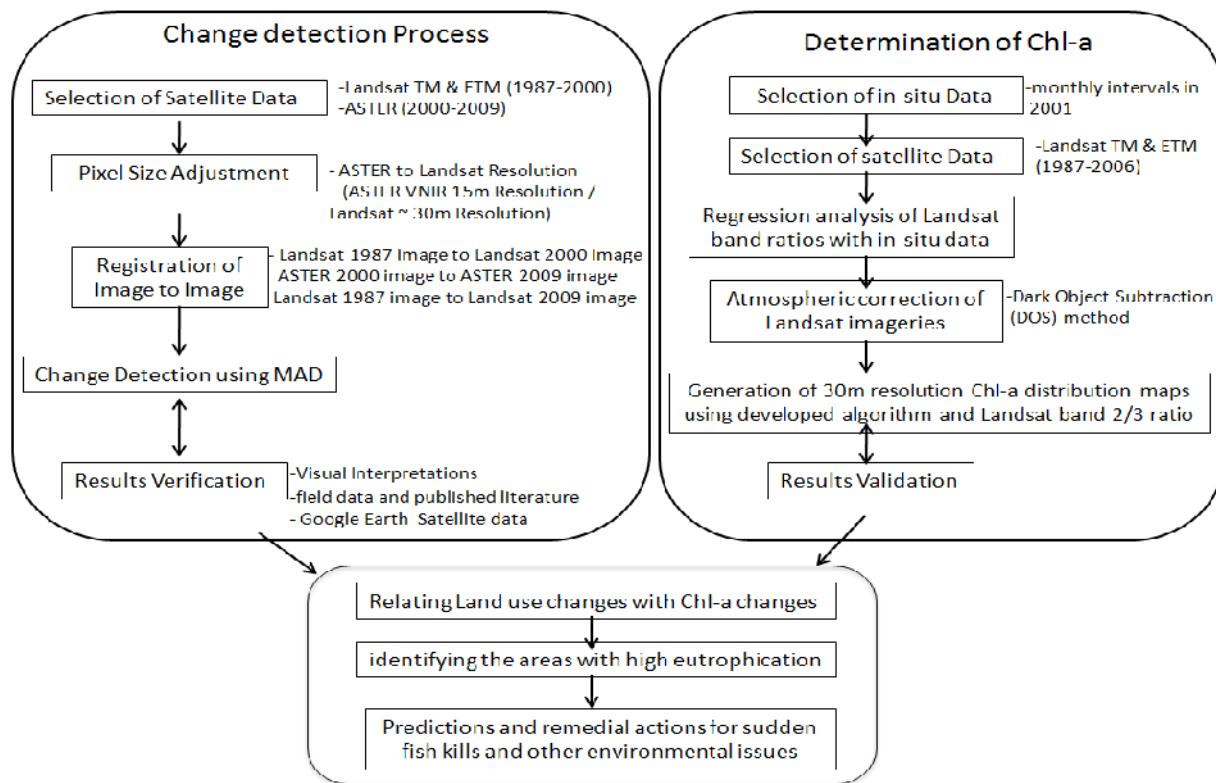
Fig. 4. Flow of the data analysis of the present study.
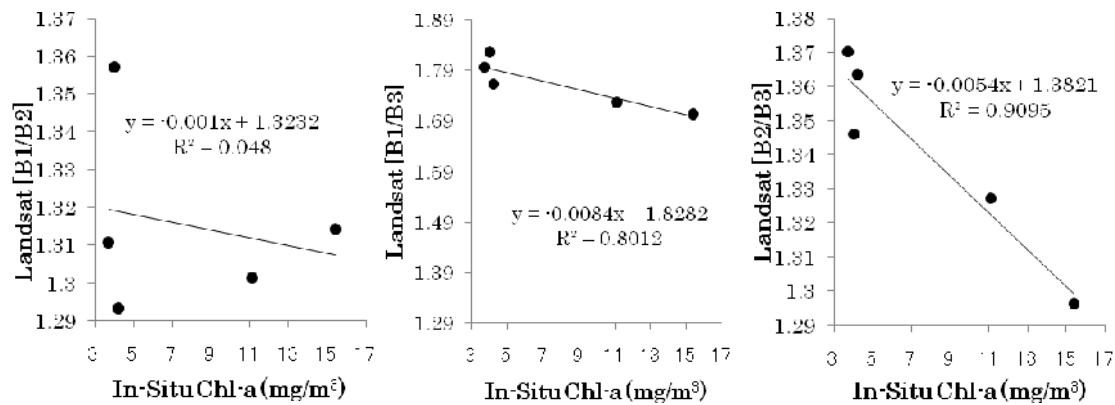
Results

The results of the MAD transformation using 19 February 1987 Landsat TM image and 16 February 2009 ASTER image are shown in Fig. 5. Maximum change areas are shown as white and black pixels. Both these zones have been subjected to changes during time interval. Grey pixels indicate no change. Significantly, changed areas are indicated as circles and their causes as detected in-situ are described in Fig. 5. According to MAD components, considerable changes in the channel segment during 1987 to 2009 could be identified with rapid changes from 2000 onwards. Significant changes that occurred during the study period at the head region of the estuary resulted in continuous narrowing of the channels. Some other changes have also taken place in this coastal environment including the change of the arable land texture, the discussion of which is beyond the scope of this study.
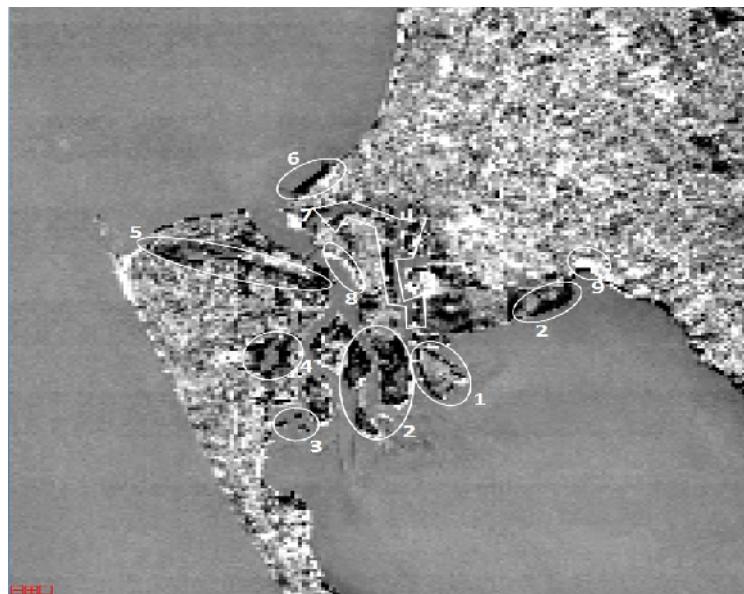

Fig. 5. MAD results (comparison between Landsat TM 19 February 1987 image with ASTER 16 February 2009 image); Maximum change areas are shown as white and black pixels. Grey pixels indicate no change.

1- Expansion of the islet area due to mangrove vegetation
2- Increase density and area of mangrove vegetation
3- Formation of new islets
4- Decrease of water area due to increase of land area and vegetation
5- Narrowing of outlets and decrease of area of Kuda ela.
6- Sand depositions (seasonally change)
7- Narrowing of east channel due to increase land area and vegetation
8- Soil erosion and vegetation area convert to land
9- Vegetation area convert to land

Fig. 6 displays the plots of the in-situ Chl-a content versus the Landsat band ratios on 14 March 2001. The highest correlation (R^2=0.91) of in-situ Chl-a content was observed with Landsat B2/B3. Similar relationship was successfully introduced by Dahanayaka et. al. (2010) to the Puttalam lagoon, Sri Lanka using ASTER B1/B2 which is similar to Landsat B2/B3. Table 2 shows the correlation coefficients for three Landsat band ratios: B1/B2, B1/B3, and B2/B3 with the in-situ Chl-a content. The correlation coefficient was highest for the Landsat band 2/3 ratio; as such, this ratio was used for generation of Landsat-based Chl-a maps. Fig. 7 shows 30 m resolution Chl-a distribution maps estimated from Landsat band 2/3 ratio using the regression equation between the in-situ Chl-a content and the Landsat band 2/3 ratio with atmospherically corrected Landsat imageries. Results indicated a significant increase in the Chl-a content in the head region of the estuary especially in Kuda Ela and Madabokka areas.

Fig. 6. Correlation between the in-situ Chl-a and the Landsat band ratios (2001.03.14).

1987.02.19   1992.02.10   1992.03.13   2000.12.15

2001.03.14   2005.02.28   2006.01.23   2006.12.09
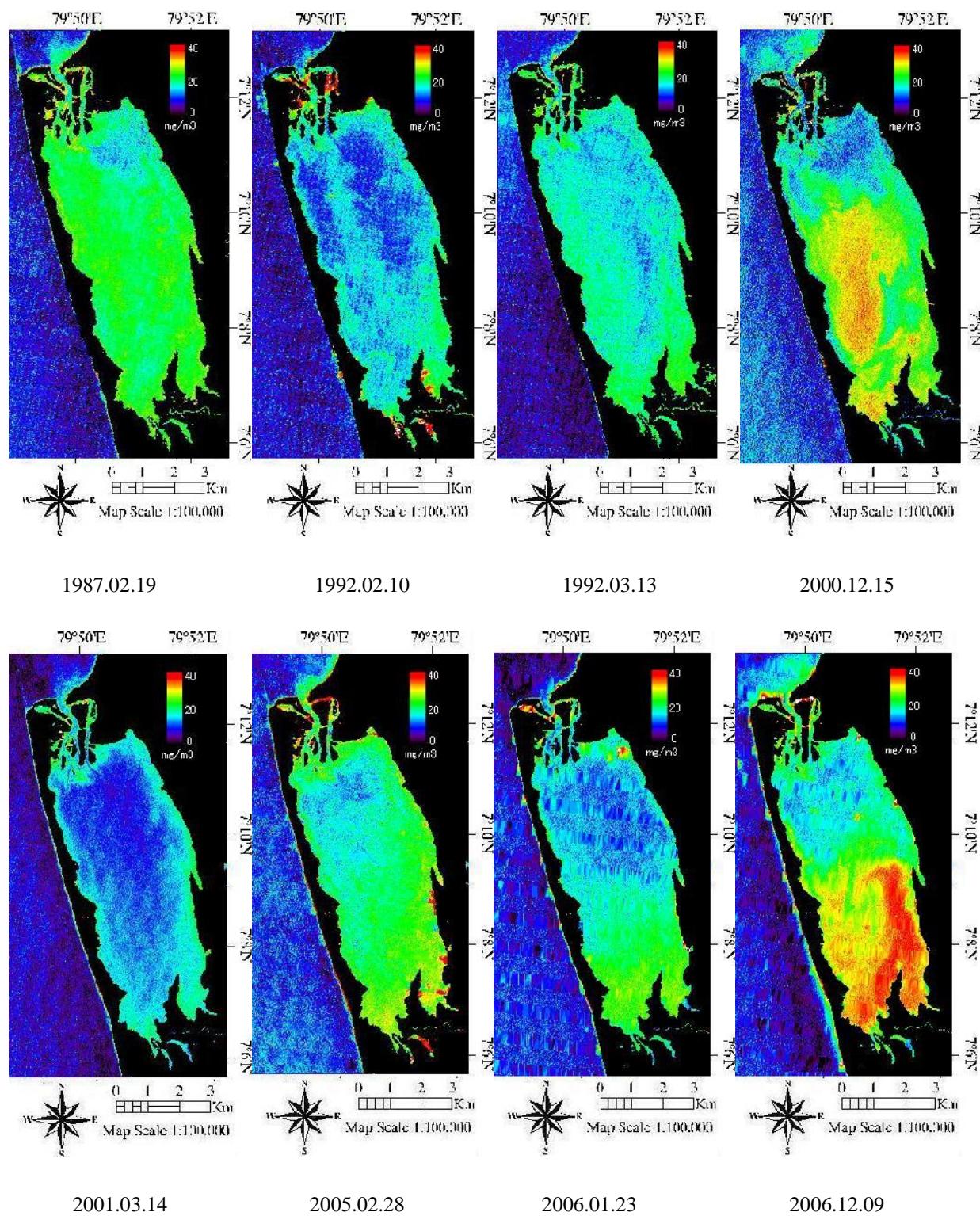
Fig. 7. Chl-a distribution maps of Negombo estuary derived from Landsat TM and ETM+ band 2/3 ratio.

Discussion

Channel segment of the Negombo estuary is very important for estuarine functions contributing to the exchange of water with the sea. However, this area is subjected to changes resulting in various anthropogenic and natural activities. Detail studies on these aspects have not been carried out although such studies will contribute significantly to identify decadal changes of the environment and fisheries of this estuary. The entrance of the estuary acts as a low pass filter, which is considerably choked in tidal amplitudes due to its narrow inlet. The tidal range in the estuary varies between 0.05 m at neaps to 0.13 m at springs, which is about 30% of the open ocean tide (Rydberg and Wickbom, 1996). The volume of water stored and released varies between 2.5×10^6 m^3 and 7×10^6 m^3 per tide with an average of about 4.5×10^6 m^3 (Samarakoon and van Zon, 1991). At high freshwater discharge, *i.e.* at more than 100 m$^3 \cdot$s^{-1}, the freshwater input is similar to the tidal flux at the entrance. It means that freshwater has a dominating effect on the water exchange during such periods, whereas the tide dominates during the low discharge. Rydberg and Wickbom (1996) estimated the residence time to be between 4 days at the maximum freshwater supply (100 m$^3 \cdot$s^{-1}) and 2 weeks at the lowest freshwater supply and neap tide. The catchment area of the rivers entering Negombo estuary namely Dandugam oya and Ja Ela is 775 km^2 (Amarasinghe et al. 1999). The average annual discharge is approximately 50 m$^3 \cdot$s^{-1}. The discharge varies from 10 m$^3 \cdot$s^{-1} during the dry season to more than 200 m$^3 \cdot$s^{-1} during rainy seasons. The monthly freshwater discharge in 1993 was 25−225 m$^3 \cdot$s^{-1}, of which 72% was from Dandugam Oya and the balance 28% from Ja-Ela. In the area where the estuary is located, the total annual rainfall is 1,993−2,040 mm and the annual mean evaporation is 1,440 mm (Rajapaksha, 1997). Evaporation and evapo-transpiration remove about 0.15 km^3 of water annually. The balance flows to the sea, mainly via the sea opening in the north of the estuary and for a lesser part through the Hamilton Canal in the southern end that opens to the Kelani River. The inflow of saline water from the sea is estimated at 1.1 km$^3 \cdot$year^{-1} through the sea opening in the north of the estuary and a considerably lower quantity through the Hamilton Canal (Samarakoon and van Zon, 1991). The salinity varies from 0 to 35 g$^\cdot$kg^{-1} (De Silva and Silva, 1979; Wijeyaratne, 1984; Rydberg and Wickbom, 1996; Rajapaksha, 1997; Arulananthan, 2004; Dahanayaka and Wijeyaratne, 2006). The exchange mechanisms maintain the salinity levels, the siltation rates, the pollution transport and the biological productivity within the estuary, and narrowing and reduction of the depth of the channels may directly affect these processes. Results of the present study clearly show such changes of the channel segment and also its impact on biological productivity in certain areas of the estuary.

According to Samarakoon and van Zon (1991), the sedimentation rate is estimated to be about 50,000 tonnes$^\cdot$year^{-1}, which results in a decrease in depth by about 1.5 mm$^\cdot$year^{-1} and the estimated filling time exceeds 400 years. However, the rate of sea level rise compensates for filling and the anticipated sea level rise will ensure its existence for the next 1,000 years

(Samarakoon and van Zon, 1991). Present results show that the disturbance of channel segment was more rapid in 2000−2009 than in 1987−2000. Such rapid changes of the channel segment may increase the sedimentation and siltation levels than that predicted by Samarakoon and van Zon (1991).

In 1991, 22% of the bottom of the estuary was recorded to be covered with sea grasses, which are very sensitive to turbidity and siltation. These areas are highly productive and provide habitats for a variety of aquatic organisms, including many commercially important shrimp and fish species (Samarakoon and van Zon, 1991). The width of sea grass beds varied from about 200 m to 2,000 m and the area covered by sea grass beds was around 900 ha in the early 1990s (Pinto and Punchihewa, 1996). Highly productive sea grass beds in the estuary play a more important role in fisheries productivity than the mangroves. Considerable decline in the extent of the sea grass beds in the recent past could be due to increased silt loading from rivers entering the estuary and poor water exchange. The sea grass ecosystems in northern, eastern and western parts of the estuary were recorded to decrease by 96% within 1997 and 2004. Disturbance of the channel segment would have altered the water exchange resulting in nutrient loading of certain water stagnant areas of the estuary. Such nutrient loading leads to dense algal proliferation affecting the distribution of sea grasses. It had been suggested that excess nutrients are trapped by macro-algae reducing the spread of sea grasses (Dahanayaka and Wijeyaratne, 2006).

The MAD results of the present study clearly indicate that the extent and density of mangroves at Kadolkele had increased during 1987 to 2009. This could be attributed to the protection provided with the acquisition of this area by the National Aquatic Resources Research and Development Agency (NARA), which is the Government institution dealing with research and development of aquatic resources in Sri Lanka.. The ditches in the adjacent, abandoned coconut plantation have been colonised by mangroves and have become a part of the adjacent mangroves. A minute increase of mangroves occurs at the seaward end of the lagoon, particularly due to the cultivated woodlots. Further, some islets in the channel segment which are managed by the Forest Department of Sri Lanka also show an increase in the extent and density of mangroves. Several other important changes which directly relate to water circulation of the estuary are also taking place continuously since 2000. These changes should be carefully monitored and early mitigations and remedial actions should be taken to avoid serious environmental issues such as water quality deterioration and fish kills that will lead to the collapse of estuarine fisheries.

Results indicated that Chl-a distribution in the Negombo estuary could be estimated using Landsat band 2/3 ratio. Chl-a is positively correlated with green band reflectance and negatively correlated with red band reflectance. Fig. 8 shows the typical spectrum due to Chl-a indicating the responsible region of Landsat bands 2 and 3. Therefore, the reflectance ratio of green and red bands becomes a robust parameter to estimate Chl-a content (Sakuno et al. 1999). Results indicated a significant increase of Chl-a content in water stagnant areas of the estuary such as

Kuda Ela and Madabokka areas during 1987 to 2009. Sudden fish kills had often been observed in Kuda Ela area during this period. Fish kills maybe due to suffocation caused by night-time oxygen depletion in the dry season. Domestic waste and waste from the fish drying industry directly enter this area resulting in high accumulation of nutrients. This, coupled with disturbance of water circulation due to narrowing of the outlet channels lead to high algal growth and finally to sudden fish kills. The areas susceptible to such fish kills due to high algal growth could be identified by high resolution Chl-a distribution maps so that remedial action could be taken in advance.
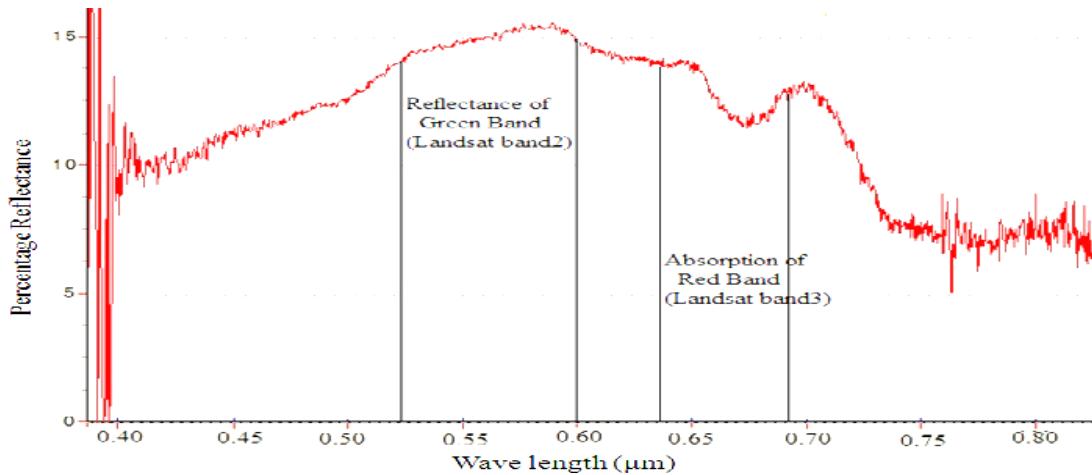
Fig. 8. Typical Chl-a Spectrum indicating responsible region of Landsat bands 2 and 3. (Spectrum developed by authors, based on spectral data recorded in Negombo estuary on 2011.03.03 using BSR112E spectrometer)

Conclusion

Results of the present study showed that information from satellite remote sensing can play a useful role in determining the changes in land area and vegetation cover in Negombo estuary and in the development of time series Chl-a distribution maps. Such information is important for the future predictions, development and management of this area as well as in the conservation of biodiversity. The study concluded that some parts of the channel segment of Negombo estuary has decreased significantly during 1987−2009 resulting in changes of water circulation which has probably affected the biological productivity through changes of Chl-a.

Acknowledgements

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