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RESEARCH PAPER

Monitoring Eutrophication Trends in Bolgoda North Lake, Sri Lanka by Satellite Remote Sensing

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Abstract

This study was aimed to determine the present level and past trends of eutrophication of the Bolgoda North lake, Sri Lanka using *in situ* Chlorophyll-a (Chl-a) measurements and remote sensing data obtained from Advanced Space-borne Thermal Emission and Reflectance Radiometer (ASTER) satellite data. From March to October 2013, Chl-a, nitrate and phosphate contents of the lake were measured once a month on the days of ASTER overpass and using standard laboratory methods. Cloud-free ASTER images of the lake for the 2000-2013 period were atmospherically corrected using Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) and *in-situ* Chl-a data were regressed with atmospherically corrected three ASTER Visible and Near Infrared band ratios of the same date. The green/red band ratio, which had the highest coefficient of determination, was used to develop algorithm for generation of 15-m resolution Chl-a distribution maps. Results indicated that eutrophication of this lake has increased from 2008 to 2011. Heavy eutrophic conditions were noted in several regions of the lake in 2013, especially in water stagnant areas and adjacent to freshwater inlets. Unplanned urbanization and inadequate facilities for waste management have resulted in heavy eutrophication of the water body. If the present trends of waste disposal and unplanned urbanization continue, enormous environmental problems would be resulted in future.

Keywords: ASTER, Bolgoda North Lake, chlorophyll-a, eutrophication, Sri Lanka.

Introduction

Although chlorophyll-a (Chl-a) is widely used as a measure of the trophic condition of water bodies (Jayasiri and Dahanayaka, 2009; Huang *et al*., 2010), it is not easy to monitor the Chl-a content over a large area continuously by conventional methods of *in-situ* sampling because of high cost, manpower and time consumed. Therefore, *in-situ* measurements do not provide sufficient information on the spatial and temporal variations of environmental parameters of aquatic systems, which are essential for their proper management (Ritchie *et al*., 2003). Chl-a determination through satellite sensors offers several advantages over traditional monitoring techniques. Because of the high altitude of the satellite large area can be monitored including the areas where accessibility is difficult or impossible (Pattiaratchi *et al*., 1994). Satellite imageries are useful also in studying past trends even when *in-situ* data are not available (Dahdouh-Guebas, 2002). Most Chl-a retrieval algorithms developed using remote sensing data are for waters where color is mainly due to Chl-a with little amount of suspended particles and dissolved color substances. However, in most coastal and inland waters suspended particles and dissolved substances also contribute to the color and interfere with the spectral signal of Chl-a (Pattiaratchi *et al*. 1994, Dall'Olmo *et al*.2005, Tzortziou *et al*. 2007). Hence satellite imageries have to be correlated with *in-situ* data (Dahanayaka *et al*., 2011,2012, 2013)

Natural eutrophication is a slow and gradual process, occurring over many centuries as nutrient-rich soil washes into lakes. However, human-induced eutrophication occurs within a short period of time (Addy and Green, 1996).Nutrients responsible for eutrophication are mainly nitrates and phosphorus as they contribute to heavy growth of algae (Bachmann, 2011).

Trophic state of water bodies has been categorized according to phosphorus concentration. Lakes with phosphorus concentrations of <10 µg/L are classified as oligotrophic lakes and those with 10-30 µg/L of phosphorous are categorized as mesotrophic lakes, while those with >30-100 µg/L of phosphorous are classified as eutrophic lakes (Bronmark and Hansson, 2005). When the dissolved oxygen concentration is low, most of the nitrates in

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deeper areas is reduced to nitrogen gas. Therefore nitrogen concentration in those lakes varies widely from 1500 µg/L to over 6000 µg/L (Bronmark and Hansson, 2005). Agricultural runoff and addition of organic wastes from various industries such as food processing plants, tanneries, textile factories and dairies result in the loading of nitrates and phosphorus into water bodies which leads to eutrophication resulting in high growth of algae (Fried *et al*.,2003; Gunatilaka and Wijeyaratne, 2009).

The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) imageries from the NASA's Terra satellite have been widely used for the estimation of Chl-a in aquatic systems (Sakuno and Matsunaga, 2002; Kishino *et al*., 2005; Nas *et al*., 2009). This is mainly because ASTER has a spatial resolution 15 m and swath width of 60 km in the visible and near-infrared (VNIR) spectral region (Yamaguchi *et al*., 1998), which is sufficiently high to target smaller water bodies, such as lakes, lagoons and estuaries.

Objective of the present study was to determine the present level and past trends of eutrophication along Bolgada North Lake using *in-situ* Chl-a content and time series Advanced Space-borne Thermal Emission and Reflectance Radiometer (ASTER) satellite data.

Materials and Methods

Study Area

Bolgoda Lake (06.40º–06.48º N; 079.55º-079.58º E) is a shallow brackish water body situated in Western province of Sri Lanka with a maximum depth of 9 m and surface area of 374 km^2 (IUCN and CEA, 2006). Bolgoda North Lake receives water from Weras Ganga and Bolgoda Ganga which originate from the South Lake and drains into Panadura estuary (Figure 1).

Salinity of the Lake which is is influenced by freshwater inflow and tidal fluxes ranges from 0 to 15 mg/ (Siriwardena and Tissa, 1988). A total of 45 Fish species, 40 Reptile species, 16 Amphibian species, 97 Avian species and 31 Mammalian species, which represents about 1/3 of total vertebrate species in Sri Lanka have been recorded from the Bolgoda Lake (IUCN and CEA, 2006). Bolgoda Lake has a subsistence and recreational fishey contributed by sea bass (*Lates calcarifer*), Mud crab (*Scylla serrata*) and sea crab (*Portunus pelagiucs*), (Silva *et al*., 2013). Even though Sri Lankan lagoon fishers get a low income, the average income of a Bolgoda lake fisher is reported to be higher than the national average due to the high catch of high valued fish (Silva *et al*., 2013). Further, when compared with other estuaries and lagoons in Sri Lanka, Bolgoda North Lake has a high potential for ecotourism, recreation and aquaculture (Silva *et al*., 2013).

Several densely populated townships, namely Moratuwa, Kesbawa and Panadura are located around this water body (Gunatilaka and Wijeyaratne, 2009). Land reclamation is taking place extensively to pave way for the construction of houses and other structures resulting in loss of lake area and sedimentation. Factories are located on either side of the Weras Ganga resulting in the pollution of lake water (Silva *et al*., 2013).

Data Collection

In situ Data

Monthly water samples were collected in triplicate from April to October 2013 from 5 sampling sites (Figure 1). The Chl-a concentration of each

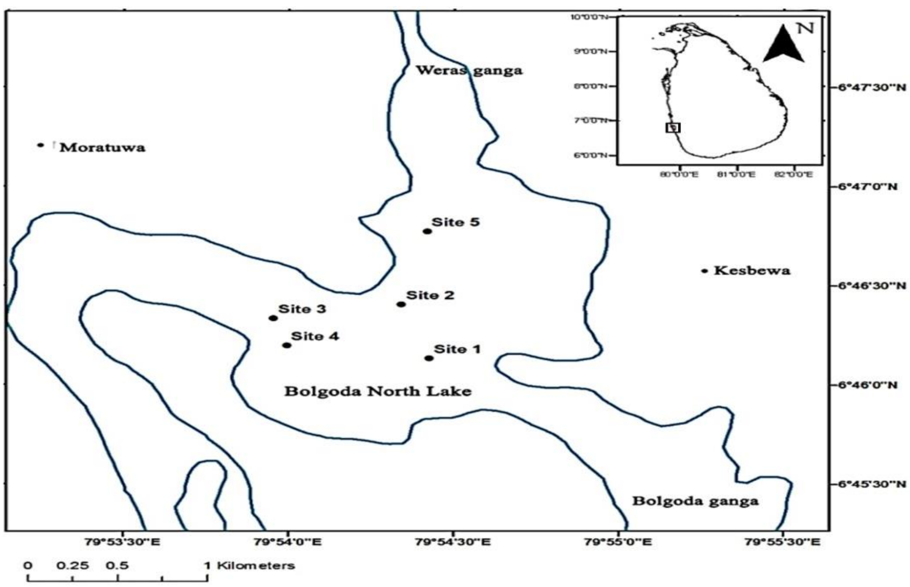

Figure 1. Map of the Bolgoda North Lake showing *in-situ* sampling sites.

sample was measured using a laboratory spectrophotometer following the method described by Aminot and Rey (2000). Nitrate and phosphate concentrations of the surface water were measured using the Ultraviolet Spectrophotometric Screening Method and the Ammonium Molybdate Spectrometric Method respectively, as described by APHA (1998).

Data Processing

ASTER imageries of Bolgoda North Lake under clear sky conditions were obtained since 2005 to determine the past trends in Chl-a contents. For accurate estimation of Chl-a content from remote sensing data, corrections have to be done for surface reflectance resulting in due to atmospheric absorption and scattering. (Cooleya *et al*., 2002). Therefore all ASTER images were atmospherically corrected using the tropical atmospheric and maritime aerosol models in FLAASH, which is one of modules mounted on the ENVI software, which is one of popular software products for remote sensing which, allows physics-based atmospheric correction with support of the radiative transfer code, MODTRAN (Berk *et al*., 1989). FLAASH is designed to obtain surface reflectance from at-sensor radiances of various hyper-spectral and multi-spectral sensors by eliminating atmospheric scattering and absorption effects of water vapor and aerosols through MODTRAN's radiative transfer modeling and other features (Cooleya *et al*., 2002).

ASTER band ratios for three spectral band pairs (B1/B2, B1/B3 and B2/B3) were calculated from the atmospherically corrected images and regressed with respective Chl-a values to determine the band ratio which gives the highest correlation and the highest coefficient of determination. The green (B1) to red (B2) band ratio (B1/B2) which showed the highest correlation and the highest coefficient of determination was used to develop the algorithm for the generation of Chl-a distribution maps. Earlier studies have also shown that B1/ B2 is a robust parameter that can be used to estimate the Chl-a content (Dahanayaka *et al.*, 2012; Dahanayaka *et al.*, 2013).

Statistics

Since data were normally distributed, parametric procedures were used in the statistical analysis. The mean values for nitrate, total phosphorus and Chl-a contents at different sampling sites were compared using two way ANOVA followed by Tukey's pairwise comparisons. Pearson's correlation coefficient between Chl-a content and nitrate and total phosphorus contents were also calculated. Simple linear regression analysis was done taking Chl-a content as the independent variable and B1/B2 band ratio, which gave the highest correlation with Chl-a content, as the dependent variable. MINITAB software package (Version 14.0) was used for statistical analysis.

Results

During the study period the Chl-a content varied from 11.45 mg/L recorded in site 1 in July 2013 to 78.40 mg/L recorded in Site 2 in April 2013 (Figure 2). However the mean Chl-a content at the five sampling sites were not significantly different from each other ($P>0.05$) (Table 1). Nevertheless, when the mean values for each month were considered, the values recorded in April and May were significantly higher than those recorded in other months ($P<0.05$) (Table 2). During the study period, the nitrate concentration of the surface water fluctuated from

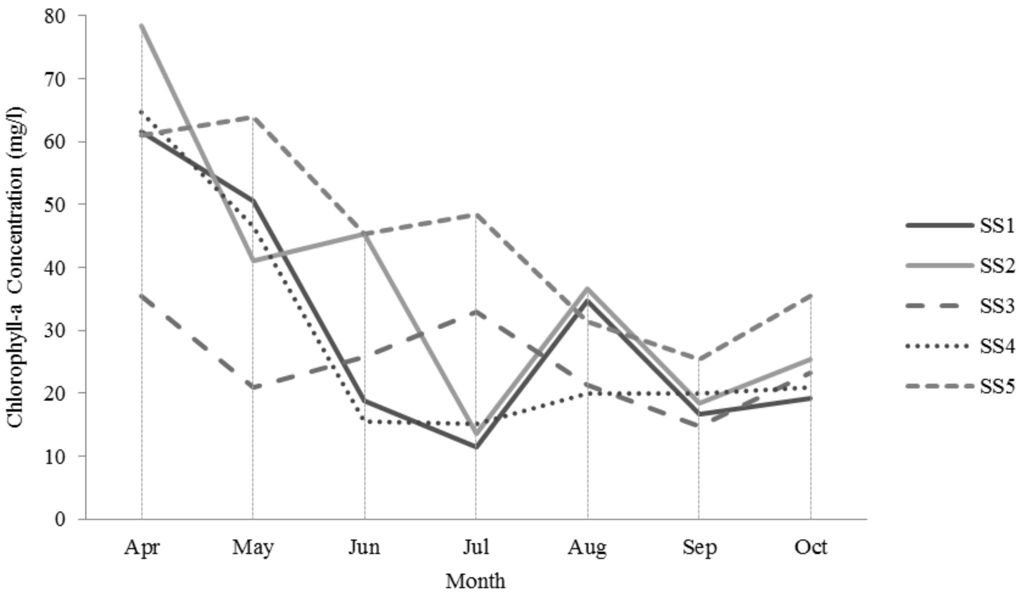

Figure 2. Monthly variation of Chl-a content at different sampling sites (SS) during the study period.

1.68 mg/L to 5.42 mg/L. The lowest value was recorded in September 2013 at sampling site 1 while the highest value was recorded in July at sampling site 2 (Figure 3). The mean values of nitrate concentration at the five sampling sites were not significantly different from each other (P>0.05) (Table 1). However, when the monthly mean values were considered, value recorded in October was significantly lower than that recorded in July (P<0.05) (Table 2). During the study period total phosphorus levels of the five sampling sites fluctuated between 21.0 μg/L and 113.0 μg/L. The lowest value was recorded in September 2013 at sampling site 1 while the highest value was recorded in the same month at sampling site 5 (Figure 4). The mean values of the total phosphorus levels in the five sampling sites were

Table 1. Mean±SEM values for Chl-a, nitrate and total phosphorus levels in the surface water at the five sampling sites of the Bolgoda North Lake. The ranges are indicated within parentheses. In each row, the values indicated by the same superscript letter are not significantly different from each other (P>0.05)

	Site 1	Site 2	Site 3	Site 4	Site 5
Chl-a content (mg/L)	30.35±7.26[a] (11.5-61.7)	37.01±8.02[a] (13.7-78.5)	24.96±2.71[a] (14.8-35.5)	28.97±7.20[a] (15.1-64.6)	42.43±5.52[a] (25.5-63.9)
Nitrate Concentration (mg/L)	2.78±0.28[b] (1.68-3.66)	3.44±0.39[b] (2.38-5.42)	2.81±0.10[b] (2.49-3.22)	3.13±0.38[b] (2.13-4.51)	3.33±0.32[b] (1.88-4.30)
Total phosphorus concentration (μg/L)	61.57±9.96[c] (21-109)	71.43±9.51[c] (39-110)	64.14±3.34[c] (54-76)	62.43±6.31[c] (36-88)	88.57±5.69[c] (74-113)

Table 2. Mean±SEM values for Chl-a, nitrate and total phosphorus levels in the surface water of Bolgoda North Lake at each month. The ranges are indicated within parentheses. In each column, the values indicated by the same superscript letter are not significantly different from each other (P>0.05)

Month	Chl-a content (mg/L)	Nitrate Concentration (mg/L)	Total phosphorus concentration (μg/L)
April	60. 24±6.96[a] (35.46-78.40)	3.05±0.22[ab] (2.46-3.58)	69.80±5.62[a] (54.00-88.00)
May	44.62±7.00[a] (21.05-63.90)	3.33±0.29[ab] (2.51-4.04)	86.40±7.85[a] (68.00-109.00)
June	30.22±6.43[b] (15.54-45.43)	2.81±0.23[ab] (2.20-3.52)	67.20±12.40[a] (36.00-110.00)
July	24.30±7.13[bc] (11.45-48.39)	3.91±0.50[a] (2.78-5.42)	60.20±8.45[a] (39.00-87.00)
August	28.81±3.43[bc] (19.95-36.57)	2.90±0.18[ab] (2.38-3.31)	79.20±6.38[a] (64.00-99.00)
September	19.07±1.82[c] (14.78-25.48)	3.46±0.49[ab] (1.68-4.33)	65.00±14.90[a] (21.00-113.00)
October	24.88±2.85[bc] (19.16-35.46)	2.24±0.11[b] (1.88-2.49)	59.60±4.76[a] (47.00-74.00)

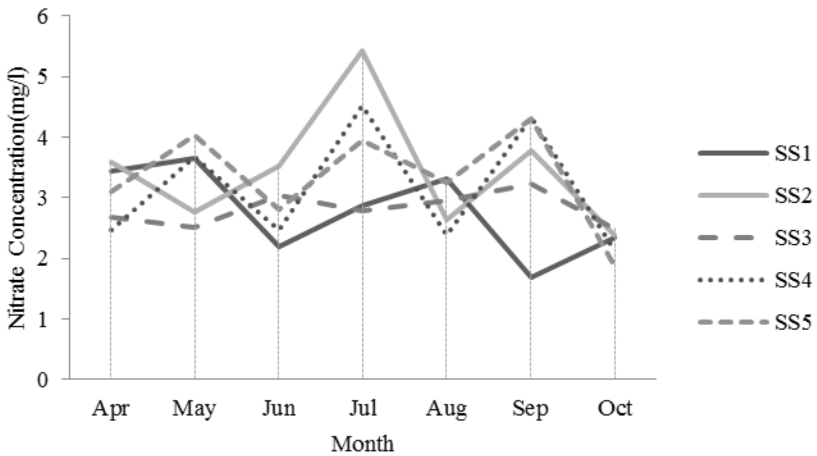

Figure 3. Monthly variation of nitrate levels at different sampling sites (SS) during the study period.

not significantly different from each other (P>0.05) (Table 1). Similarly, there were no significant difference in the mean values of different months (P>0.05) (Table 2).

The highest value for correlation coefficient, which was -0.884 was recorded between B1/B2 band ratio and Chl-a content (p = 0.000) (Table 3). The coefficient of determination indicated that 78% of the total variation of the relationship between Chl-a content and the B1/B2 band ratio is explained by the linear regression model (Figure 5). When Chl-a content was regressed with band ratios B1/B3 and B2/B3 although the correlation coefficients were significant (p=0.000) (Table 3), only 47% and 61% of the variability around the regression line were explained respectively. Therefore the regression equation between Chl-a content and B1/B2 band ratio was used to generate ASTER-based Chl-a maps for the Bolgoda North Lake.

Figure 6 shows the 15m resolution Chl-a distribution maps derived using the regression equation between the *in-situ* Chl-a and the atmospherically corrected ASTER B1/B2 ratio. Results indicate that there is very little eutrophication in the lake in 2005 and this has increased gradually until 2013, In April 2013, some regions of the Weras Ganga and Bolgoda river which flow into the lake showed high Chl-a concentrations above 90 mg/L indicating hypereutrophic conditions. In June, September and October also those areas showed Chl-a concentrations above 30 mg/L indicating eutrophic conditions. These areas were found to be bordered by industrial zones. Field investigations showed that these areas receive water from nearby factories through some canals. Some areas in the north eastern region of the lake, which also contain more or less stagnant water were also highly eutrophic. In this area, several cottages of low income groups exist. In June and September the intensity of eutrophication in the areas of Weras Ganga and Bolgoda Ganga had reduced which that of the middle region of the lake has increased slightly. In October, 2013 eutrophication of the lake had further decreased (Figure 6).

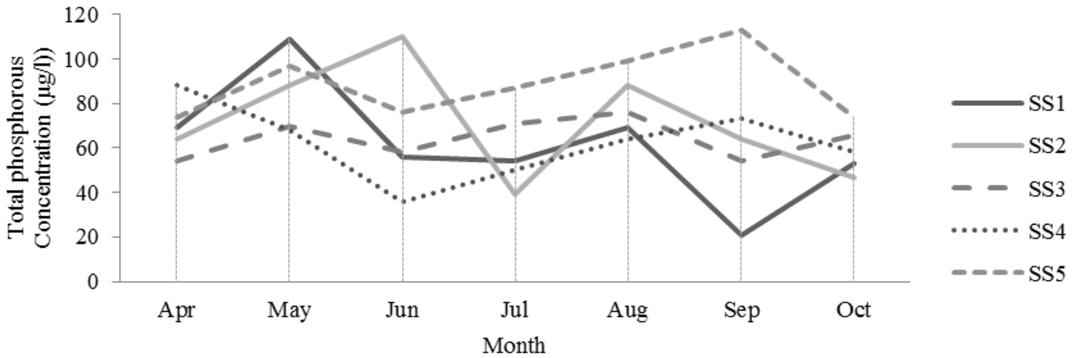

Figure 4. Monthly variation of total phosphorus levels at different sampling sites (SS) during the study period.

Table 3. Pearson's correlation coefficients (r) of Chl-a content with nitrate and phosphate levels and B1/B2, B21/B3 and B2/B3 band ratios (P=Level of significance)

	Nitrate Content	Total phosphorus content	B1/B2	B1/B3	B2/B3
r	0.125	0.514*	-0.884*	-0.668*	0.781*
p	0.474	0.002	0.000	0.000	0.000

* Significant at 5% level (P<0.05)

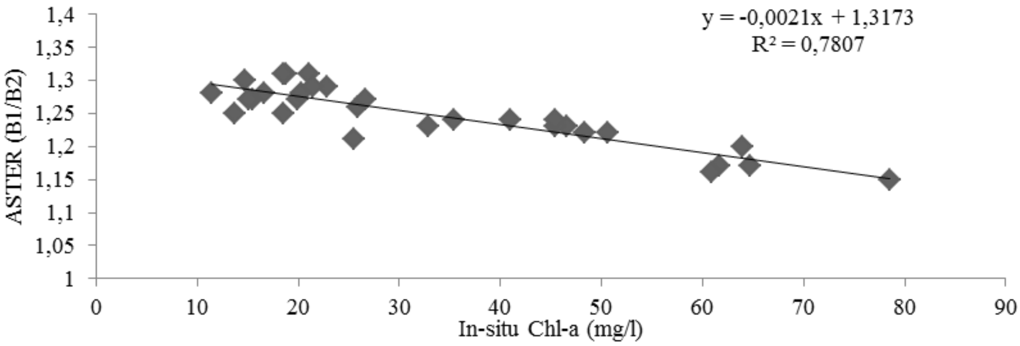

Figure 5. Regression analysis between the *in-situ* Chl-a and the ASTER B1/B2 band ratio.

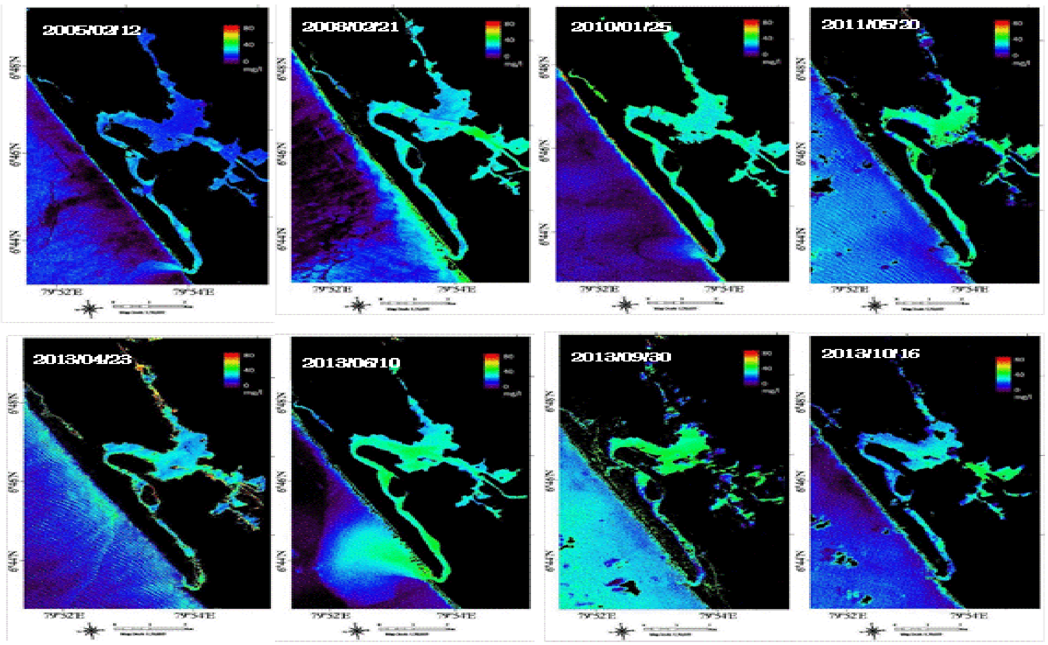

Figure 6. Chl-a distribution maps of Bolgoda North Lake derived from ASTER band 1/2 ratio.

Discussion

The results indicated that Chl-a distribution and areas of eutrophication in the Bolgoda North Lake surface waters can be reliably estimated using the ASTER B1/B2 band ratio, calibrated with matchup *in situ* data. The reflectance ratio between B1 (green) and B2 (red) is a useful parameter to estimate Chl-a because Chl-a concentration is positively correlated with the reflectance in the green spectral range and negatively correlated with reflectance in the red spectral range (Sakuno *et al*., 1999). Further, earlier research on remotely sensed monitoring of Chl-a concentration in Sri Lankan coastal water bodies such as the Puttalam Lagoon, the Negombo estuary and the Chilaw Lagoon has also shown that the highest correlation with Chl-a concentration was obtained with the ASTER B1/B2 ratio. (Dahanayake *et al*., 2011, 2012, 2013). Since Chl-a content is widely used as an indicator of eutrophication (Jayasiri and Dahanayake, 2009, Fried *et al*., 2003), Chl-a distribution maps developed using ASTER imageries could be used to identify the areas of eutrophication of the Bolgoda North lake also.

Chl-a content showed a significant positive relationship with total phosphorus content ($P<0.05$) indicating that the high nutrient loading with phosphorus specifically is likely one of the reasons for the eutrophication of the lake. Increased phosphorous levels could be the cause for high growth of phytoplankton which is indicated by high Chl-a levels. However, Chl-a content did not show a significant correlation with the nitrate content of the surface waters of the lake ($P>0.05$). This is in contrary to the findings of Balali *et al.* (2013) who reported that there is a significant negative correlation between Chl-a and nitrate content in Alma Gol Wetland in Iran.

Mean values for Chl-a content, nitrate concentration and total phosphorus concentration of the sample sites were not significantly different from each other (Table 1). Similarly there were no significant differences in the mean total phosphorus concentration among different months according to the measured values at the five sampling sites (Table 2). However, when the ASTER imageries developed for the entire water body indicates that the Chl-a content vary temporally and spatially throughout the study period. This clearly indicates that ASTER imageries are very useful to get a holistic view whereas the *in-situ* sampling gives only a limited picture.

Many industries, which discharge waste into the lake through canals that flow into the rivers that open to the lake are located in this region (Gunatilaka and Wijeyaratne, 2009). Most of these factories do not have effective waste treatment systems. Such waste would have contributed to high nutrient contents resulting in high Chl-a contents leading to hypereutrophic conditions in the Weras Ganga and Bolgoda Ganga closer to the place where they join the lake. On the lands bordering the northwestern region of the lake where hyper-eutrophic conditions were noted, there were crudely built cottages of low income groups. Those dwellings lack proper sanitary facilities and therefore sewage, animal waste and household waste are directly released in to the lake. This would have resulted in high amount of nutrients in those areas. Generally inadequately treated sewage is considered to be a significant source of phosphorus. Domestic sewage is considered to be the most significant pollutant dumped into this water body, followed by waste water and trade effluent from nearby factories (Nawoda and Ranasinghe 2012). According to the Chl-a distribution maps developed through ASTER data, hyper-eutrophic conditions were observed mainly in April, i.e., just before the onset of southwest monsoons. Due to less rainfall during this period, the nutrients would have been concentrated in these water stagnant areas resulting in heavy growth of algae. However, such a high concentration of nutrients was not observed in the five sampling sites where the water was not stagnant in these areas (Figs 3 and 4) and therefore were less eutrophic (Figure 6). In June and September 2013, hyper-eutrophic conditions in Weras Ganga and Bolgoda Ganga were reduced possibly due to flushing with the rain water of southwest monsoons. However, during this period, eutrophic conditions in the mid region of the lake have increased in April (Figure 6) probably because the nutrients have washed away into this region. In October 2013, the eutrophic conditions have further reduced probably due to further flushing of most nutrients due to southwest monsoonal rains. Hence it is evident from the results that the intensity of eutrophication of this lake varies temporarily due to the variation in rainfall pattern.

IUCN and CEA (2006) reported that the Bolgoda North Lake is disturbed due to release of industrial effluents from textile factories, saw mills and furnishing factories and also due to pesticides and fertilizers used in agriculture and domestic activities, increase of tourism related activities etc. Due to the scenic beauty of the Bolgoda Lake, tourism related activities including hotel construction have also been increased in the recent past (SCCP, 2002). Intensification of these activities may be the reason for increased eutrophication observed in some regions of the Bolgoda North Lake since 2005.

The results of the present study demonstrated that information from satellite remote sensing can play a useful and unprecedented role in determining the trends of eutrophication in Bolgoda North Lake in the western coastal region of Sri Lanka, specifically through the development of time series Chl-a concentration maps coupled with knowledge on the spatial distribution of land use and industrial activities. Hence, this remote sensing technique is useful to identify the areas of heavy eutrophication so that relevant action could be taken on time for the conservation management of this ecologically and economically important aquatic system.

Acknowledgments

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