Int. J. of Sustainable Water & Environmental Systems
Volume 8, No. 2 (2016) 93-100

Integrating in Situ Field Measurements and Satellite Remote Sensing to Monitor Eutrophication Trends in Bolgoda North Lake, Sri Lanka

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Abstract

This study focused on determining eutrophication trends in Bolgoda North Lake, Sri Lanka using *in situ* Chl-a measurements and ASTER satellite data. From March to October 2013, water samples were collected from five sampling sites almost once a month coinciding with ASTER overpasses. Chl-a, nitrate and phosphate concentrations were measured using standard laboratory methods. ASTER images were atmospherically corrected using FLAASH and *in situ* Chl-a data were regressed with three ASTER VNIR band ratios from the same date and location. As a result, the regression equation of the green/red band ratio, which resulted in the highest correlation with Chl-a (R^2 = 0.78), was used to generate Chl-a maps during the 2000-2013 period. Eutrophication has gradually increased over the period 2008-2011 and significant high conditions noted throughout the year 2013 in several regions, especially in stagnant water areas. If the present trends of waste disposal and unplanned urbanization continue, enormous environmental problems can be expected in the future. Present study demonstrates that information from satellite remote sensing can play a useful role in the development of time series Chl-a maps, which is important for the monitoring, development and management of this area as well as in the conservation of the water body.

Keywords: *Aster, Bolgoda Lake, Chlorophyll-a, Eutrophication, Sri Lanka*

1. Introduction

Agricultural runoff and the addition of organic wastes from various industries, such as food processing plants, tanneries, textile factories and dairies result in nutrient loading to water bodies [0],[**Error! Reference source not found.**]. The increase in nutrient concentrations in aquatic environments is generally referred to as eutrophication. 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 [**Error! Reference source not found.**]. Nutrients that are usually associated with eutrophication, and as such are commonly measured and monitored in water bodies, are nitrates and phosphorus.

Increased nutrient concentrations can lead to detrimentally high concentrations of algal biomass in water bodies with implications throughout the ecosystem [**Error! Reference source not found.**],[**Error! Reference source not found.**]. Chlorophyll-a (Chl-a) is a proxy for algal biomass and has been long applied as a measure of the trophic condition of water bodies [**Error! Reference source not found.**],[0],[0]. However, the regular monitoring of Chl-a concentrations over large areas by conventional methods of in situ sampling is limited because of the high associated cost, manpower and time

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DOI: 10.5383/swes.8.02.010

required. Furthermore, in most instances a single or a few samples is not sufficiently representative of the entire water body [0]. Therefore, in situ measurements and the collection of water samples for laboratory analyses to evaluate water quality parameters do not provide sufficient information on their spatial or temporal variations, which are essential to understand for the proper management of aquatic systems [0].

Chl-a determination through satellite sensors offers several advantages over traditional monitoring techniques for water bodies. The high altitude and resulting large swath width of a satellite allows us to monitor large areas simultaneously and provides comprehensive records of regional features, rendering the procedure cost-effective in comparison to conventional monitoring programs. Satellite observations can be applied to areas that may otherwise be inaccessible to investigators [0], often provide regular measurements in time due to their repeat overpasses, and also allow the study of past trends even when in situ data are not available [0]. Although most Chl-a retrieval algorithms which have been developed using remote sensing data are for oceanic Case 1 waters, which are characterized by water-leaving spectra dominated by the Chl-a signature of phytoplankton and have little inorganic suspended particulate matter (SPM) or colored dissolved organic matter (CDOM), coastal and inland waters can almost invariably be classed as Case 2 waters, where inorganic SPM and CDOM also contribute significantly and variably to the water-leaving spectra and interfere with the spectral signal of Chl-a in the water [0],[0],[0]. Chl-a retrieval algorithms are increasingly successfully applied in Case 2 settings. However the high degree of variability between such sites as well as the characteristic optical complexity renders this challenging and site-specific algorithm calibration is often required [0],[0].

Nutrient enrichment and the resulting intense algal blooms have been identified as a severe threat to Bolgoda North Lake in Sri Lanka, which is an ecologically and economically important natural resource. Therefore, the objectives of the present study are to develop remote sensing products specifically adapted to monitor the eutrophication of the lake and to highlight eutrophication trends in time and space through the examination of multi-year time series maps. In situ Chl-a measurements are used to calibrate Chl-a retrieval algorithms applied to Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) imagery, and measurements of in situ nutrient concentrations as well as the spatial distribution of local land uses provide further context to the findings.

2. Methodology

2.1. Study Site

Bolgoda Lake (06.40^0 – $06.\ 48^0$ N; $079.\ 55^0$- $079.\ 58^0$ E) is a shallow brackish waterbody situated in the Western Province of Sri Lanka [0]. The maximum depth of the lake is 9 m and its surface area, including both the South and North Lakes, is approximately 374 km^2. Bolgoda North Lake is fed by the Weras Ganga, which brings water from the north, and the Bolgoda Ganga, which brings water from Boldoga South Lake (Figure 1). The outflow of water from Bolgoda North Lake to the Laccadive Sea is via the Panadura estuary. A detailed bathymetric study of the lake was conducted by Siriwardena and Perera (1986) [0]. Salinity of the lake water, which has been found to range from 0 to 15 mg/L, is influenced by freshwater inflow and tidal fluxes [0]. A total of 45 fish species, 40 reptile species, 16 amphibian species, 97 avian species and 31 mammalian species, which represent approximately one-third of the total vertebrate species in Sri Lanka, have been recorded from the Bolgoda Lake [17]. Bolgoda Lake is famous for angling of sea bass (*Lates calcarifer*), Mud crab (*Scylla serrata*) and sea crab (*Portunus pelagiucs*), which are of high economic value [0]. Although Sri Lankan lagoon fishermen typically earn a low income, the average income of a Bolgoda Lake fisherman is reported to be higher than the national average due to the high catch volume [0]. Further, when compared with other estuaries and lagoons in Sri Lanka, Bolgoda North Lake has a high potential to contribute to ecotourism, recreation and aquaculture [0].

The lake is located in a mixed land use area with industrial and some agricultural activity, low, middle and high income housing, and tourist hotels. Several densely populated townships, namely Moratuwa, Kesbawa and Panadura are located around the lake [**Error! Reference source not found.**]. Extensive land reclamation is taking place to allow the construction of houses and other structures, resulting in the loss of lagoon area and the increased sedimentation of the water. Factories are located on either side of the Weras Ganga which flows into the lake and bioaccumulation of contaminants in fish and organic pollution is reported [0].

2.1. Data Collection

2.2.1. 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 sample was measured using a laboratory spectrophotometer following the method described by Richards & Thompson (1952) [0] and Aminot & Rey (2000) [0]. 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) [0].

2.2.2. Aster Data

The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) onboard the NASA Terra satellite was used as the high resolution sensor for the analysis. ASTER has three spectral bands with a spatial resolution of 15 m and a swath width of 60 km in the visible and near-infrared (VNIR) spectral region [0]. Although the spectral positions of ASTER/VNIR were not designed for water color observations in aquatic systems, several such investigations of Chl-a estimation have been carried out using ASTER data [0],[0],[0],[0],[0],[0] because ASTER has a spatial resolution that is sufficiently high to target smaller water bodies, such as lakes, lagoons and estuaries. A total of 22 ASTER scenes acquired since 2000 over Bolgoda North Lake under clear sky conditions were collected for Chl-a estimation (Table 1). In all cases, ASTER level-1B products (registered radiance at the sensor products) were used as input data.

Table 1. ASTER observation dates for Bolgoda North Lake.

Year	Date
2000	28th October
2005	12th May
2007	18th February
2008	21st February, 08th March, 30th December
2009	31st January, 16th February, 28th September, 24th December
2010	25th January, 14th March

2011	13th February, 1st March, 20th May
2013	27th February, 23rd April, 10th May, 26th June, 05th July, 30th September, 16th October

2.3 Data Processing

2.3.1. Atmospheric Correction

The accurate retrieval of Chl-a or other water constituent concentrations from remote sensing data first requires the accurate estimation of surface reflectance through modeling and removing the effects of atmospheric absorption and scattering. Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) [0], available from Exelis Visual Information Solutions Inc. as part of the ENVI image processing software, was used for this purpose. FLAASH carries out a physics-based atmospheric correction with the support of MODTRAN radiative transfer code [0] and is designed to obtain surface reflectance from at-sensor radiances of various hyper-spectral and multi-spectral sensors [0]. All ASTER images used in this study were atmospherically corrected using FLAASH, applying the tropical atmospheric and maritime aerosol model options.

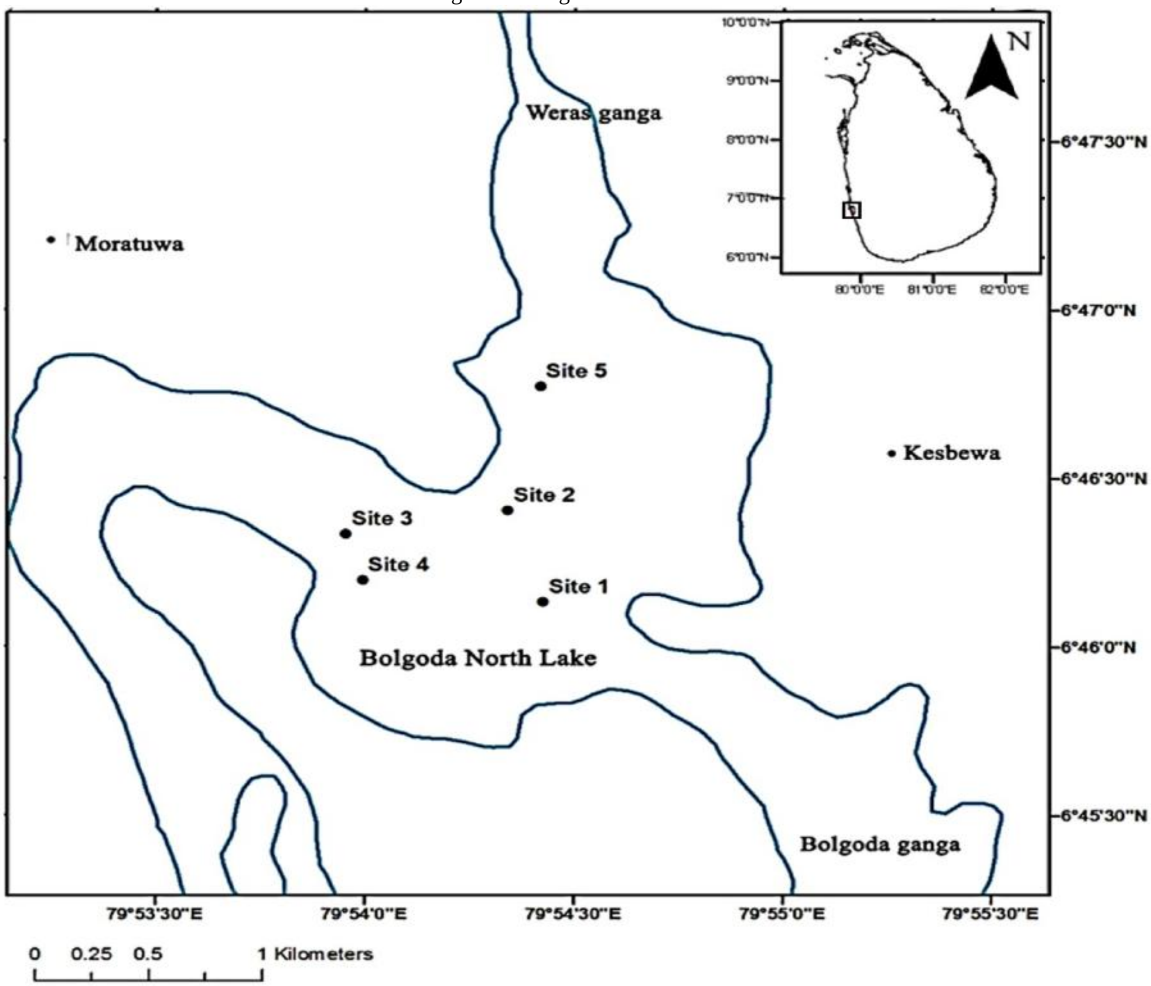

Fig. 1. Map of the Bolgoda North Lake Showing the Five *in Situ* Sampling Sites

2.3.2 Spectral Band Ratios

Band ratios for all three ASTER spectral band pairs were calculated from the atmospherically corrected images and regressed with the coinciding *in situ* Chl-a data to determine the band ratio which resulted in the highest correlation. Image reflectance values were extracted for regression analysis using the average of 3 x 3 kernels from the same coordinates as the *in situ* measurements from the same day.

2.3.3 Statistical Analysis

The Anderson-Darling test was used to determine whether the data conformed to a normal distribution. Since the data did not vary significantly from a normal distribution, parametric tests were used in the statistical analysis. The mean values for nitrate, total phosphorus and Chl-a concentrations at different sampling sites were compared using Analysis of Variance (ANOVA). The Pearson's correlation coefficients were also calculated between Chl-a concentrations and nitrate and total phosphorus concentrations. Simple linear regression analysis was done with Chl-a content as the independent variable and the ASTER B1/B2 band ratio as the dependent variable. The MINITAB version 14.0 software package was used for these statistical analyses.

3. Results

During the study period, the Chl-a concentration varied from 11.5 mg/L (recorded in site 1 in July 2013) to 78.46 mg/L (recorded in site 2 in April 2013) (Figure 2). However, the mean Chl-a concentrations of the five sampling sites were not significantly different from each other ($p > 0.05$) (Table 2). The nitrate concentration of the surface water ranged from 1.68 mg/L to 5.42 mg/L, and the lowest value was recorded in September 2013 at sampling site 1, while the highest value was recorded in July 2013 at sampling site 2 (Figure 3). The mean nitrate concentrations of the five sampling sites were not significantly different from each other ($p > 0.05$) (Table 2). Total phosphorus concentrations of the five sampling sites ranged between 21.0 µg/L and 113.0 µg/L, and 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 total phosphorus concentrations of the five sampling sites were also not significantly different from each other ($p > 0.05$) (Table 2).

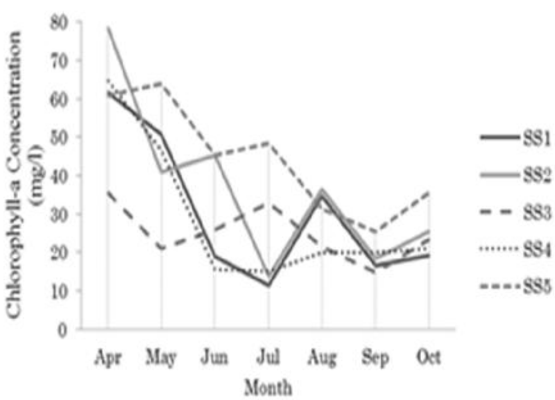

Fig. 2. Monthly Variation In Chl-A Concentration at Each Sampling Site (SS) During the 2013 Study Period.

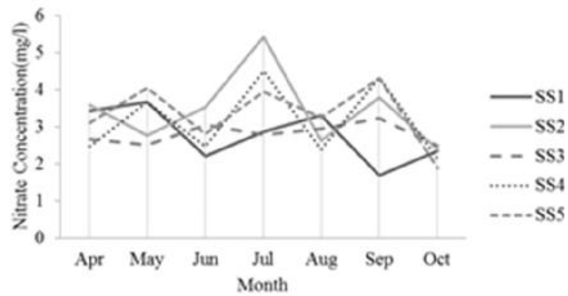

Fig.3. Monthly Variation in Nitrate Concentration at Each Sampling Site (SS) During the 2013 Study Period.

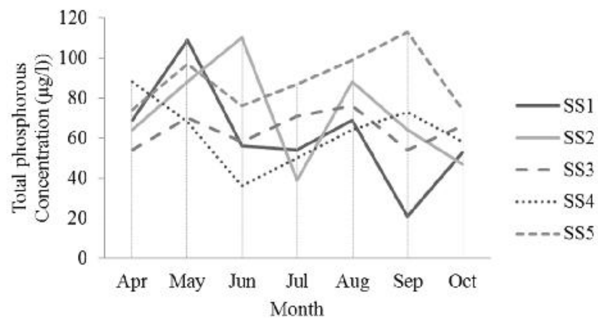

Fig. 4.Monthly variation of total phosphorus levels at different sampling sites (SS) during the 2013 study period.

The highest absolute value of the correlation coefficient (r) was -0.884 which was obtained between the ASTER B1/B2 band ratio and Chl-a concentration ($p = 0.000$) (Table 3). This shows that the B1/B2 band ratio significantly and consistently decreases as Chl-a concentration increases. The corresponding coefficient of determination (R^2) indicates that 78% of the total variation of the relationship between Chl-a concentration and the B1/B2 band ratio is explained by the linear regression model (R^2=0.78, Figure 5). When the Chl-a concentration was regressed with band ratios B1/B3 and B2/B3, only 47% and 61% of the variability around the regression line were explained respectively. Therefore the regression equation between the Chl-a concentration and the B1/B2 band ratio was used to generate ASTER-based Chl-a maps for the Bolgoda North Lake.

Table 2. Mean±SEM for Chl-A, Nitrate and Total Phosphorus Concentrations in the Surface Water of the Five Sampling Sites of the Bolgoda North Lake. The Full Ranges Measured Over The 2013 Study Period are in Parentheses.

	SS1	SS2	SS3	SS4	SS5
Chl-a (mg/L)	30.35±7.26 (11.5-61.7)	37.01±8.02 (13.7-78.5)	24.96±2.71 (14.8-35.5)	28.97±7.20 (15.1-64.6)	42.43±5.52 (25.5-63.9)
Nitrate (mg/L)	2.78±0.28 (1.68-3.66)	3.44±0.39 (2.38-5.42)	2.81±0.10 (2.49-3.22)	3.13±0.38 (2.13-4.51)	3.33±0.32 (1.88-4.30)
Total phosphorus (µg/L)	61.57±9.96 (21 - 109)	71.43±9.51 (39 - 110)	64.14±3.34 (54 - 76)	62.43±6.31 (36 - 88)	88.57±5.69 (74 -113)

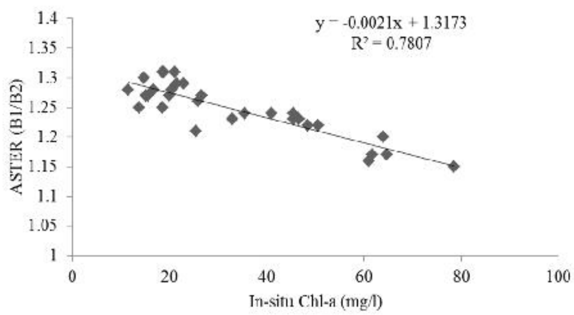

Fig. 5. Regression Analysis Results between the *In Situ* Chl-A and the Aster B1/B2 Band Ratio

Table 3. Pearson's Correlation Coefficients (R) between Chl-A Concentration and Nitrate and Phosphate Concentrations and B1/B2, B21/B3 And B2/B3 Band Ratios (P = Level of Significance).

	Nitrate (mg/L)	Total phosphorus (µg/L)	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 6 shows the 15m resolution Chl-a distribution maps produced using the regression equation between the *in situ* Chl-a and the atmospherically corrected ASTER B1/B2 ratio. The results indicate that there is significant eutrophication in the Bolgoda North Lake throughout the 2013 study period. Considerable spatial heterogeneity was revealed, with higher concentrations of Chl-a recorded in stagnant water areas adjacent to freshwater outlets. Some localized eutrophication was observed in the Weras Ganga which flows into the lake. The results also indicate that there is a gradual increase in the Chl-a concentration during the 2005-2008 period and a relatively rapid increase during the 2008-2011 period.

In 2013, most areas of Bolgoda North Lake were eutrophic, with higher concentrations of Chl-a recorded in stagnant water areas. In April 2013, some regions of the Weras Ganga which flows into the lake showed Chl-a concentrations greater than 90 mg/L, indicating hypereutrophic conditions. In June, September and October of the same year, those areas also showed Chl-a concentrations greater than 30 mg/L, indicating eutrophic conditions. These areas were found to neighbor industrial zones.

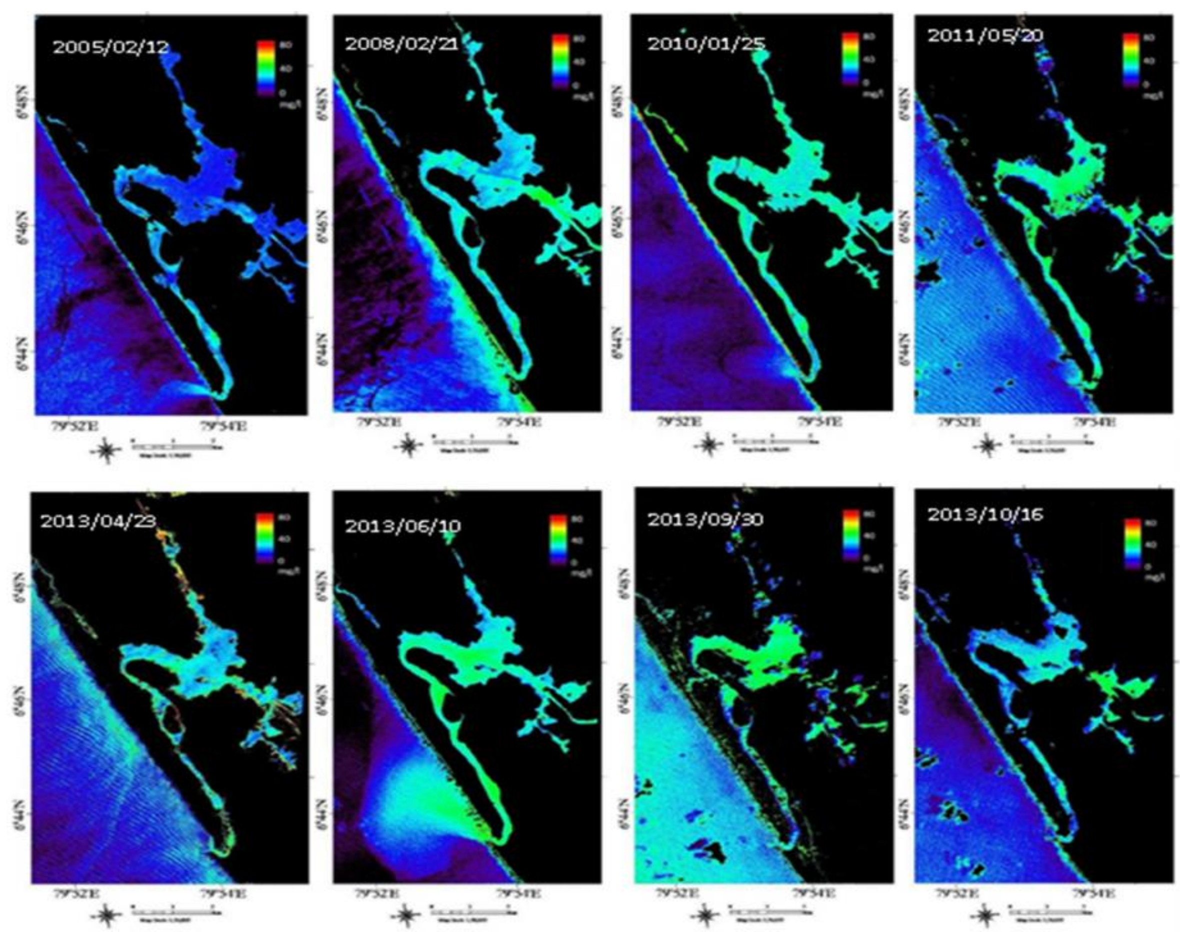

Figure 6. Chl-A Concentration Maps of Bolgoda North Lake Derived from ASTER Band 1/2 Ratio.

4. 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 [0]. 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 [0],[0],[0]. There is much industrial activity in the Ratmalana and Moratuwa areas, which discharge waste into the Bolgoda North Lake through the existing canal system. Some factories are also located on either side of the Weras Ganga, from Kaudana to Katubedda [**Error! Reference source not found.**]. Most of the factories in the Ratmalana area do not use effective waste treatment systems and thus release their waste directly into the Bolgoda North Lake. Such waste would be expected to contribute to high nutrient concentrations, resulting in high Chl-a concentration (high phytoplankton biomass) and leading to eutrophic conditions in those areas. High Chl-a concentrations were also reported in the lake areas neighboring land with crudely built cottages of low income groups. Since those dwellings lack proper sanitary facilities, sewage, animal waste and household waste are directly released into the lake, leading to high amounts 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 released into this water body, followed by waste water and trade effluent from nearby factories [0]. Mean nitrate and total phosphorus concentrations were greater than 2.78 mg/L and 61.57 µg/L respectively in all sampling sites (Table 2). *In situ* data revealed that sampling site 5 had the highest mean Chl-a (44.43 mg/L) and mean total phosphorus concentrations of all sites (88.57 µg/L) (Table 2). Chl-a concentration displayed a significant positive relationship with the total phosphorus concentration ($p < 0.05$), indicating that the high nutrient loading of phosphorus specifically is likely one of the reasons for the eutrophication of the lake. There is a significant positive relationship between Chl-a concentration and total phosphorus concentration, as the algal biomass (indicated by Chl-a) responds strongly to phosphorus in ecosystems where the nutrient availability is the primary determinant of algal biomass. Therefore, increased phosphorous levels could be the cause for high growth of phytoplankton, which is indicated by high Chl-a levels. However, Chl-a concentration did not show a significant correlation with the nitrate concentration of the lake surface waters ($p > 0.05$). This is in contrast to the findings of Balali *et al.* (2013) [0], who reported that there is a significant negative correlation between Chl-a and nitrate content in Alma Gol Wetland in Iran. When the land use pattern is considered, the agricultural lands around the Bolgoda North Lake are of considerably less importance compared to home gardens. Some of the paddy fields adjoining the lake have now been reclaimed for housing and other construction purposes. Therefore, the use of fertilizer around the lake is low. This may be the reason for low nitrate input to the lake resulting in a non-significant correlation between the Chl-a content and the nitrate level.

Field observations showed that this lake receives discharge from various factories. Unplanned urbanization and the inadequacy of waste management facilities in the nearby industries have resulted in the eutrophication of the water body. The present study indicates that the main sources of eutrophication of Bolgoda North Lake are residential waste and industrial effluents. IUCN & CEA (2006) [0] 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, the increase in tourism-related activities, etc. Due to the scenic beauty of the Bolgoda Lake, tourism-related activities including hotel construction have also increased in recent years [0]. These activities have reduced both the areal extent and the depth of the lake, leading to frequent flooding in the area in addition to increased eutrophication [0]. Intensification of these activities may be the reason for increased eutrophication observed in some regions of the Bolgoda North Lake during 2008-2011 in this study. An increase in nutrient loading could result in an imbalance in the food webs, threatening the ecological balance in the aquatic environment through increased phytoplankton productivity leading to eutrophication. 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. Such information is important for the future development and management of this area while conserving the environment.

Acknowledgments

The authors wish to thank Japan Space Systems (JSS), Tokyo for supplying original ASTER data, which were used in this study. Financial assistance provided by the Graduate School of Science and Engineering of the Ibaraki University, Japan and Department of Zoology, University of Kelaniya, Sri Lanka is also acknowledged with deep gratitude. We would also like to thank Ms. Stephanie Palmer for her valuable comments on this manuscript.

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