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Estimating and Mapping Chlorophyll-*a* Concentration as a Function of Environmental Changes in Lake Manzala, Egypt using Landsat 7 ETM+ Image

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Abstract

This study is aiming at developing a robust methodology for estimating Chlorophyll-*a* (Chl *a*) concentration in one of the largest coastal lakes of Egypt, Lake Manzala, using Landsat 7 ETM+ data. Lake Manzala is one of the economically valuable inland lakes in Egypt. It continuously suffers from excessive human impacts. Laboratory analyses in this research highlighted that; Lake Manzala shows high value and great spatial variation of nutrients. Nitrate concentration ranged from 1.9 to 12.3 $mgL^{-1}$with lower values towards the sea connections indicating the processes of adsorption and sedimentation, plant assimilation and flushing through the El Gamil outlet. However, the mean value of dissolved oxygen ranged from 11.8 mgL^{-1} at the eastern/southern part of the lake compared to 9.4 mgL^{-1} at the western side. Such lower values provide further evidence of eutrophication and decomposition of excess organic matter. The Landsat image was geometrically and radiometrically corrected, which subsequently converted into irradiance at sensor. The remote sensing methodology based on band ratioing and regression modelling established from *in-situ* measurements and the irradiance. Single band ratioing, particularly the visible bands 1, 2 and 3, were used to establish a correlation regression model. Ratio of ETM+ band 1 and ETM+ band 3 shown the most significant ratio in estimating chlorophyll *a* with a maximum correlation coefficient of $R^2 = 0.75$. This ratio was further verified using the Chl *a* values of the extra sampling points and was then used to estimate the spatial distribution of Chl *a* along the whole lake. Both methodology (laboratory analyses and satellite estimation) indicated high level of Chl *a* at the western and southern parts of the lake due to the effect of the drainage inflow. The produced regression model is recommended to be validated by applying onto another similar water bodies with more sampling and validating sites.

Keywords: Chlorophyll-a, Phytoplankton, Remote Sensing, Lake Manzala, Egypt.

1. Introduction

Healthy environmental conditions and water quality of inland lakes are of great importance in most countries in arid region. These coastal lakes constitute Egypt's most important wetland, which show a great public interest for fisheries, aquaculture, recreation, industry and support to most of the local communities. Unfortunately, most of these lakes are aggressively affected by the environmental changes due to both natural processes and anthropogenic activities; therefore improved timely monitoring of these lakes is urgently required. Conventional water quality measurements are based on water sampling and laboratory measurements, which surely give accurate values. It is, however, time consuming and not cost effective. More importantly, field sampling always fails to give the synoptic view together with the complete spatial coverage of the water quality parameters such as chlorophyll-*a* (Brivio *et al.,* 2001).

Phytoplankton blooms in such environment is merely due to the amount of sewage and fertilizers (e.g. nutrients and phosphorous) discharged from both urban settlement and agricultural surroundings. The interaction of Chl *a* and the electromagnetic radiation gives scattering or/and absorption with strong absorption between 400 - 500 nm (which correspond to ETM+ Band 1) and at 680 nm (which correspond to ETM+ Band 3), and maximum reflectance at 550 nm (which correspond to ETM+ Band 2) (Dekker *et al.*, 1991; Han, 1997).

Optical remote sensing techniques are widely applied in water quality studies nowadays, for example, measuring water clarity, surface temperature and Chl *a* (Giardino *et al.*, 2001, Lathrop, 1992; Zhang *et al.*, 2003). Band ratioing models are recently introduced to this field as an advantageous method to measure Chl *a*. The strength of this ratio models is reducing the influence of atmospheric illumination (Jensen, 2005; Han and Jordan, 2005). Due to the relationship between absorption and scattering of the visible spectrum and Chl *a* concentrations; therefore it is more efficient to use a ratio between two bands that have such interaction with the spectra (Gin *et al.*, 2002).

Using remote sensing technology in aquatic research worldwide is an emerging capability that can greatly replace traditional *in-situ* methods (Mittenzwey *et al.*, 1992; Braga *et al.*, 2003; Chang *et al.*, 2004). However, it is considered to be a relatively new approach especially in addressing optically complex water bodies, satellite remote sensing potentially offers a promising alternative for scientists and practitioners for assessing a large water body in an economical and timely fashioned technique. The 1st GEO workshop (Group Earth Observation) held on 27th March 2007 mainly focused on the urgent need of improving the capabilities of remote sensing in assessing and monitoring inland and near shore water quality. The final report of the workshop addressed six major issues the top most of which was the satellite sensors and its improvement to help in monitoring the inland water qualities. Till then improved techniques with using optical remote sensing is urgently needed to monitor such aquatic environments.

Lake Manzala is a highly dynamic system, today; it is very different from its original state. Its morphology has been transformed from an open water body to semi-closed sub-basins in the last few decades. Such morphological changes lead to great changes in water quality that consequently lead to flourishing of phytoplankton community in some basins. The lake is classified as an eutrophic water body (El-Sherif and Gharib, 2001; Abdelkarim, 2009; Rasmussen *et al*., 2009) with both macrophytes and planktonic algae contributing to extensive carbon fixation (UNDP, 1997). Dominance of some phytoplankton species might seriously affect the basin and alter its natural habitat (e.g. toxic species). Monitoring and mapping phytoplankton community (indicated as chlorophyll biomass) using optical versus flurometrical measurements helps in detecting environmental changes occurring throughout the lake and consequently helps in supporting decision makers in managing such economically valuable resources (Dewidar and Khedr, 2001; Abbassy *et al.*, 2003).

This research uses the visible spectrum of the Landsat 7 ETM+ data in combination with *in-situ* field sampled measurements of Chl *a* to estimate and map Chl *a* along the lake (Lake Manzala) with a sensible estimation of the lake water surface and the top level of the water column.

2. Area of Study

Lake Manzala is the largest of the Nile Delta lakes; it occupies the North Eastern corner of the Nile Delta. It lies between 31° N and 31° 30′ N and 31° 45′ E and 32° 15′ E. It is surrounded by the Suez Canal to the east, the Nile River (Damietta Branch) to the west and the north is bounded by the Mediterranean Sea and to the south agricultural and urban settlements (Figure 1). The lake is relatively shallow with a maximum depth of 3.5 m in the north near the outlet to the Mediterranean Sea and a minimum depth of 0.6 m in the western part of the lake. The average dominant depth of the lake is 1.2 m.

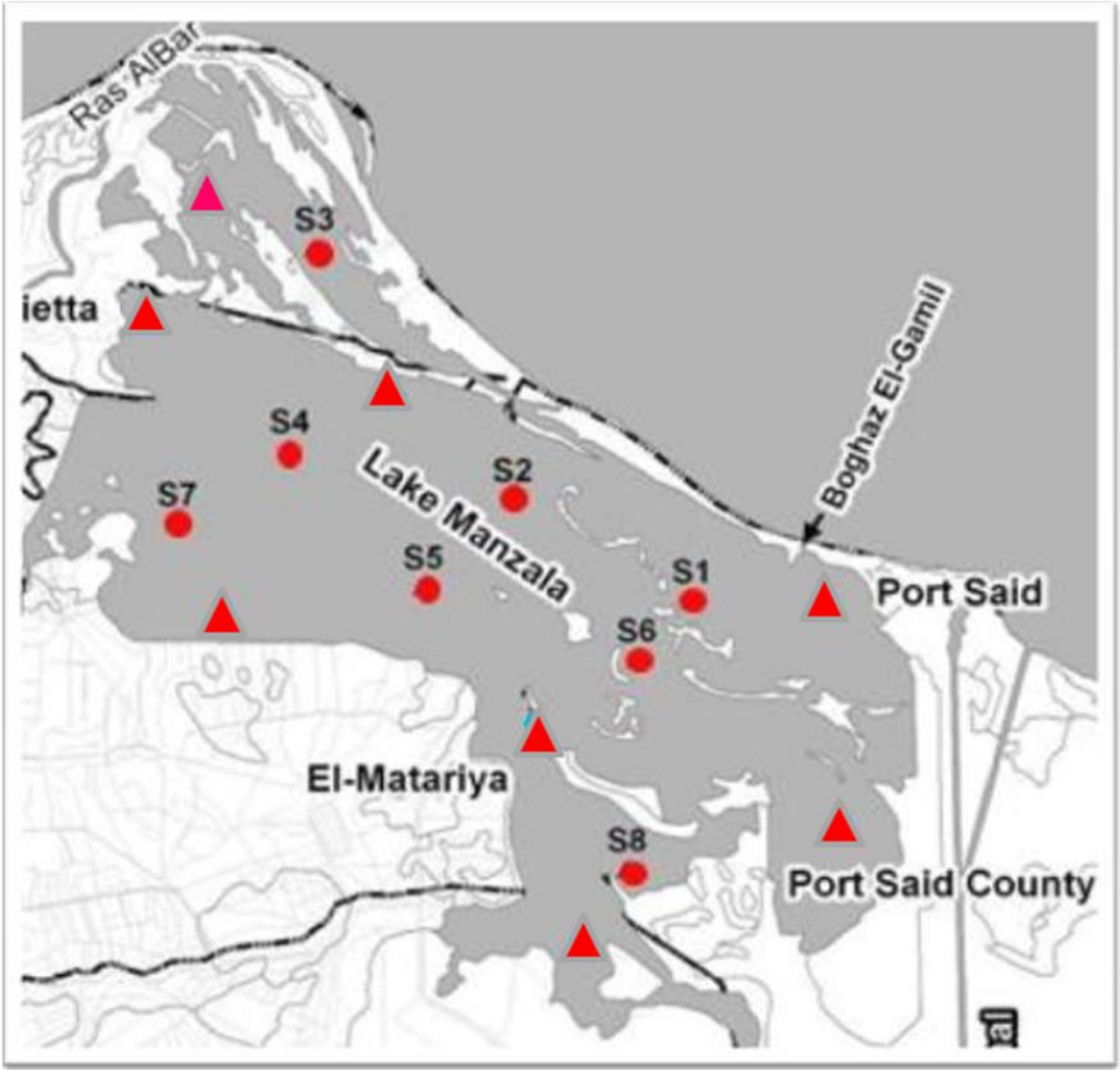

Figure 1. Area of study and sampling locations: (circles indicating the sampling sites that been used to produce the model – triangles indicating the sampling sites that been used to validate the model)

3. Methodology

3.1. Image Processing

Landsat 7 ETM+ satellite image (path 176 and row 38) acquired on 4^{th} March 2007. The image was acquired under nearly clear sky with 0.15 % of cloud cover. The optical resolution of the image is the typical Landsat image of six multi-spectral bands, which covers the visible spectrum (0.40 - 0.70 µm) and infrared (0.7 – 2.09 µm). The ground resolution is 30 meters which is adequate for such application.

The approach used in this research is focused on the visible light spectrum that gives a sensible estimation of the top level of the water column Chl *a* only rather than estimation of the surface Chl *a*. This is based on the fact that visible spectrum has the potential of penetrating water column (Han *et al.*, 1997; Jensen, 2000).

Satellite image was geometrically corrected to the UTM (Universal Transverse Mercator) grid reference (Zone 36N; Datum: WGS84). Viewer to viewer process is used to rectify the image using topographic maps with well known ground control points on both viewers. The minimum root mean square (RMS) error achieved was lesser than 0.5 pixel. Then, the image is radiometrically corrected using the darkest pixel theory (Campbell, 1993). Last the reflectance values were converted to at-sensor irradiance and surface albedo (Irish, 2000) which made the image ready for further interpretation and analysis.

A 3 x 3 window was established around each sampling location based on the UTM coordinates determined with a GPS (Global Positioning System) during the water sampling (Figure 1). The mean reflectance of the 3 x 3 window was extracted and used in the statistical modelling process (Table 1). The reasons behind the 3 x 3 window instead of a single pixel are:

1. to avoid the possible errors in the geometric correction and the dynamicity of the water body,
2. to give spatial variability of the sampling window

3.2. In-situ sampling data collection

Discrete water sampling was carried out during the satellite overpath (on 4th March 2007) with two hours discrepancies one hour before and one hour after the image capturing (i.e. 4th March 2007). Eight sampling locations distributed along the lake were chosen to represent the whole lake environment (Figure 1 – circle dots). Extra eight sampling sites were sampled for further validation of the produced model (Figure 1 – triangle dots). For water quality measurements, water samples were collected from the subsurface water column by hand dipping a one-liter sample bottle. Water samples were collected from eight selected sampling locations (two sampling bottles for each site), then taken to the laboratory and filtered prior to Chl *a* and physicochemical parameters measurements. All measurements for the eight sampling sites were conducted in duplicates (for each bottle/site) and data were then represented as a mean value. Sampling locations were geographically identified using Global Positioning System (GPS) to be superimposed on the satellite image. An assumption is made that quality of water along the lake is relatively stable or at least is not changed significantly during the imaging time.

3.2.1. Chlorophyll a estimation

Samples for Chlorophyll *a* analysis were filtered (50 ml) through 25-mm diameter GF/F filters and immediately frozen. Chlorophyll *a* was extracted in 8 mL of 90% acetone by sonication followed by centrifugation. Chlorophyll *a* was measured using a Turner AM10 fluormeter. Chlorophyll *a* concentration was determined using Parsons' equation (Parsons *et al.,* 1984) and the fluormeter calibrated against a standard Chlorophyll *a* solution (Sigma Ltd.).

3.2.2. Estimation of physic-chemical parameters

Water temperature, pH, electric conductivity, total dissolved solids (gl^{-1}) and dissolved oxygen were measured using Quanta sound probe instrument. A high precision Guideline salinometer was used for *in situ* salinity measurements. Water clarity (transparency) was assessed by Secchi disc. Dissolved oxygen was determined by the azide modification of the Winkler method (according to APHA, 1995).

Before analysis, samples were filtered through 47 mm GF/C filters (nominal porosity 1.2 mm). Laboratory analyses were made using a LKB 4050 spectrophotometer according to standard procedures (Parsons *et al*., 1984) and results were expressed in mg l^{-1}. Nitrates were analysed using a Burkard Scientific SFA-2 Auto-analyser, as described by Hydes (1984). Nitrate was reduced to nitrite using a reduction column of copper coated cadmium wire (Nydal, 1976).Total phosphorus (TP) was also assayed by spectrophotometry after reaction with ammonium molybdate and reduction by ascorbic acid (Murphy and Riley, 1962).

3.3. Statistical regression model

A regression model was established based on the albedo reflection from the satellite image and both single band ratioing and logarithmically transformed band ratioing with the Chl *a* concentration (Han and Rundquist, 1997). Correlation coefficient was then generated from both models to simulate and map the spatial distribution and concentration of Chl *a* in the lake from the satellite image.

4. Results and discussion

4.1. Water quality parameters

Water temperature showed slight variation between sampling sites during the sampling day ranged from 20.1 to 22.9 °C (Figure 2). Highest temperature values were recorded at the north western sites (sites 3, 4 and 7) and was also relatively high at the southern site (site 8). pH values ranged between 8.42 and 9.19 on the sampling day. Highest pH values were generally recorded at eastern sites; however the maximum values (8.4 and 9.1) were recorded at sites number S4 and S5, respectively (Figure 2). A similar temperature and pH trend has been previously recorded for the lake at this time of the year (e.g. Ramadani *et al*., 2009).

Dissolved oxygen varied between (8.5 – 13.2 mgL^{-1}) with a mean value of 10.6 mgL^{-1}. The maximum dissolved oxygen value was recorded at the eastern/southern part of the lake (sites 1, 6 and 8) with a mean value of 11.8 mgL^{-1} compared to the western side (sites 3, 4 and 7), which showed a mean value of 9.4 mgL^{-1}. It is likely that the lower dissolved oxygen values provide further evidence of eutrophication and decomposition of excess organic matter.

Figure (3) shows the changes of salinity, transparency and total dissolved salts (TDS) versus changes in Chl a. A noticeable variation in surface water salinity (as PSU measured by salinometer,) was recorded between sampling sites during the sampling day with a mean value of about 5.1. Minimum salinity values were recorded at the eastern and western sites (see Figure 3) however the northern and north eastern sites represent the more saline water bodies.

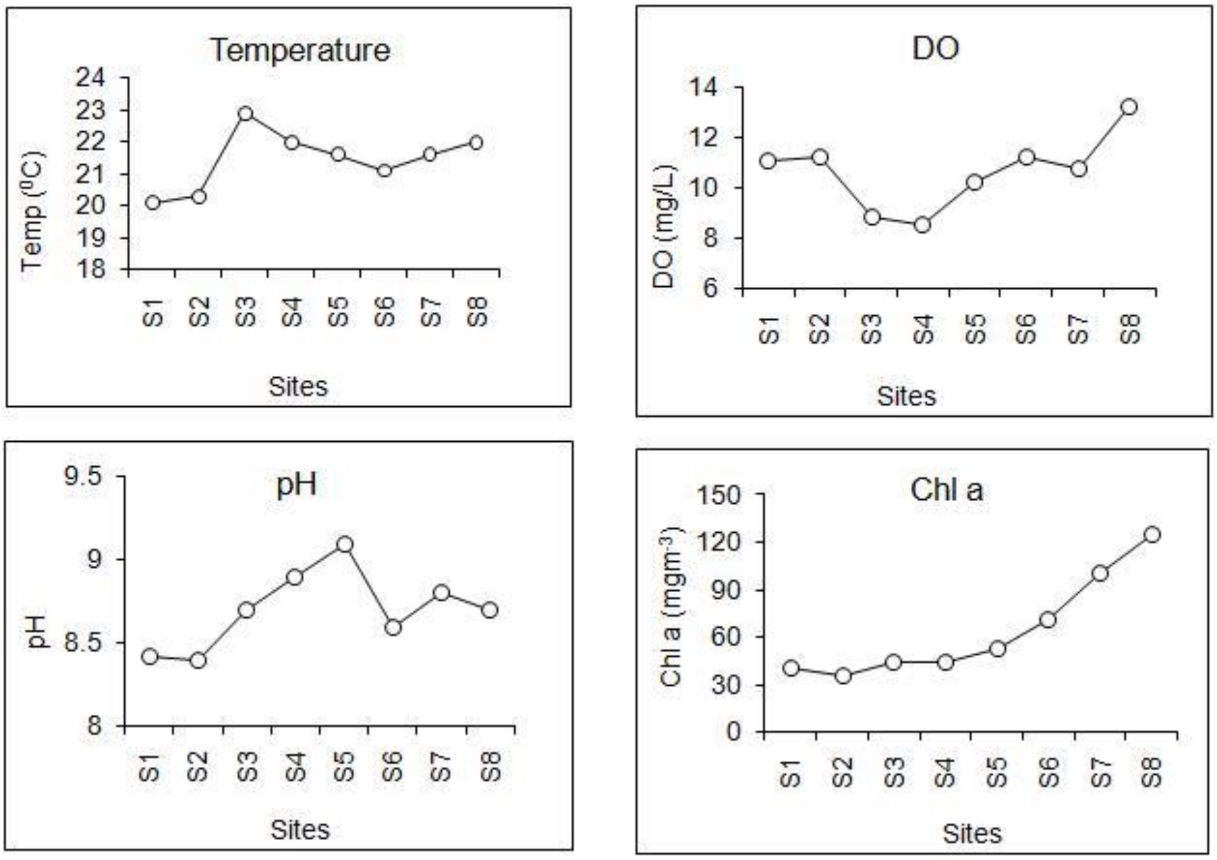

Figure 2. *In-Situ* values of temperature, pH, s, transparency and dissolved oxygen in Lake Manzala on 4th March 2007.

This shows the contribution of the Mediterranean Sea via the lake tidal inlet (Boghaz El-Gamil). Similar pattern was recognised for Total Dissolved Salts (TDS) data. Results showed that mean values of TDS varied from a minimum of about 2.0 mgL^{-1} to a maximum of 7.0 mgL^{-1} with a spatial distribution pattern similar to the salinity. This finding showed an agreement with earlier investigations (e.g. see Rasmussen, *et al*., 2009).

Water transparency data showed a remarkable variation between sampling sites (Figure 3) during the sampling day (24.0 – 90.0 cm). The northern and the eastern part of the lake showed homogenous water body with a relatively similar transparency level. Two highly transparent water bodies were recorded southwards (site 5 and site 8). Field observations together with earlier studies (e.g. Ramadani *et al.*, 2009) indicated that Lake Manzala is currently switching from a submerged macrophyte-dominated clear water system to a turbid phytoplankton-dominated system in accordance to the alternative equilibrium state theory (Scheffer *et al.*, 1993, Scheffer, 1998). In those areas that have retained submerged macrophytes communities, the water was very clear (S5 and S8) and the emergent macrophyte beds offered protection from high winds. However, elsewhere in the Nile Delta lagoons, particularly at S1 and S2, water transparency is generally low due to their shallowness, frequent sediment re-suspension as well as to high phytoplankton productivity (Mageed, 2006). A strong negative correlation ($r > 0.7$, $p < 0.05$) was detected between transparency and both salinity and TDS (Figure 4). This finding shows an agreement with earlier study (Rasmussen *et al.*, 2009) but contradicting it with regard of salinity.

Results of this research highlighted that Lake Manzala shows high values and great spatial variation of nutrients. This could be attributed to its great size and various array of nutrient sources, (Ramadani, *et al*., 2009). The concentrations and distribution of total phosphorus (TP) indicated (see Figure 5) the pattern of drainage water distribution in Lake Manzala. In addition contaminated freshwater is undoubtedly a major source of nutrients concentrations of the total phosphorus varied from a minimum of 5.2 mgL^{-1} (particularly, at S4) to a maximum of 13.1 and 12.6 mgL^{-1} at S6 and S8, respectively).This finding is mainly attributed to the fact that Within Lake Manzala, the Bahr El Baqar Drain is known as the main source of urban waste water with high concentrations of total phosphorus and nitrate (Fathi *et al*., 2001; Mageed, 2006). In general, Guerguess (1993) and Ahmed *et al.* (2009) identify the drains as the main source of phosphate to the lake. Higher concentrations of total phosphorus generally occurred in the southern and eastern zones of the lake (near to the drainage canals and to the wastewater treatment works). Data presented here indicate that the nutrient-rich drainage water is diluted and distributed across the lake in a northerly direction, and the. Nitrate concentrations (see Figure 5) were also relatively high in stations near the drains. Nitrate concentration widely varied throughout the sampling sites with a range of 1.9 -12.3 mgL^{-1}. Data showed that nutrient salt concentrations are relatively low towards the sea connections (e.g. S2 and S4). This finding probably indicates several processes: adsorption and sedimentation, plant assimilation and flushing through the El Gamil channels (Ramadani *et al*., 2009).

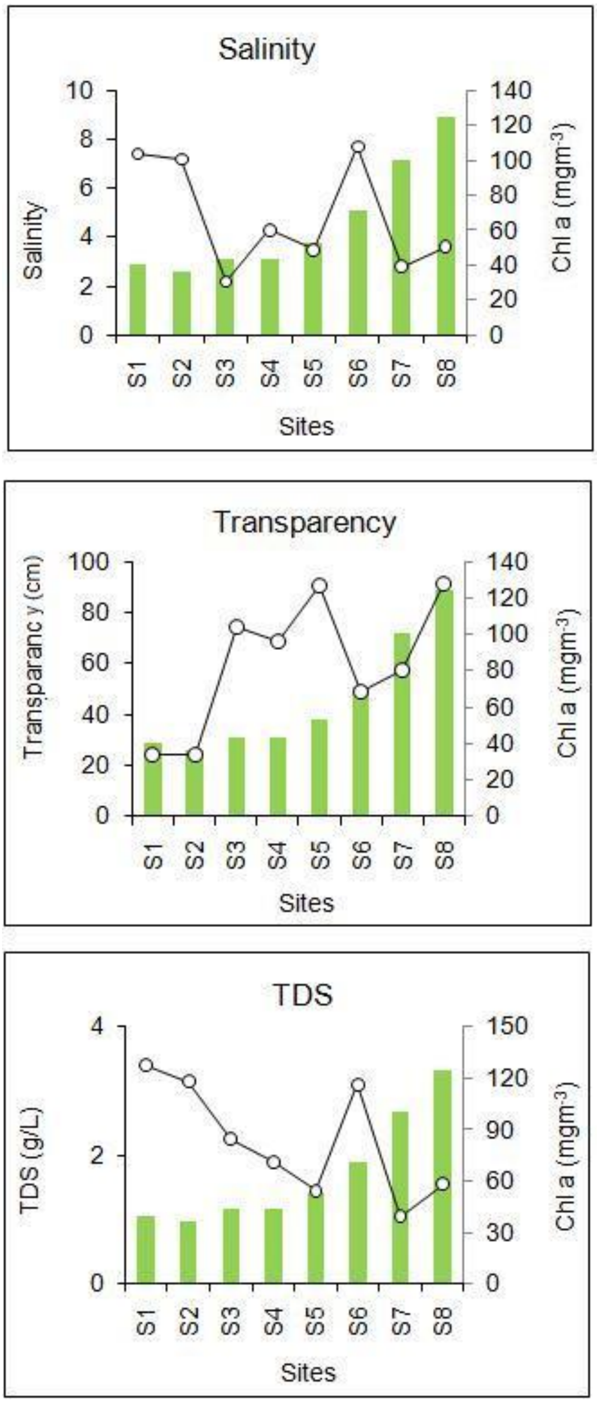

Figure 3. *In-Situ* values of salinity, transparency and total dissolved salts against Chl a values in Lake Manzala on 4th March 2007.

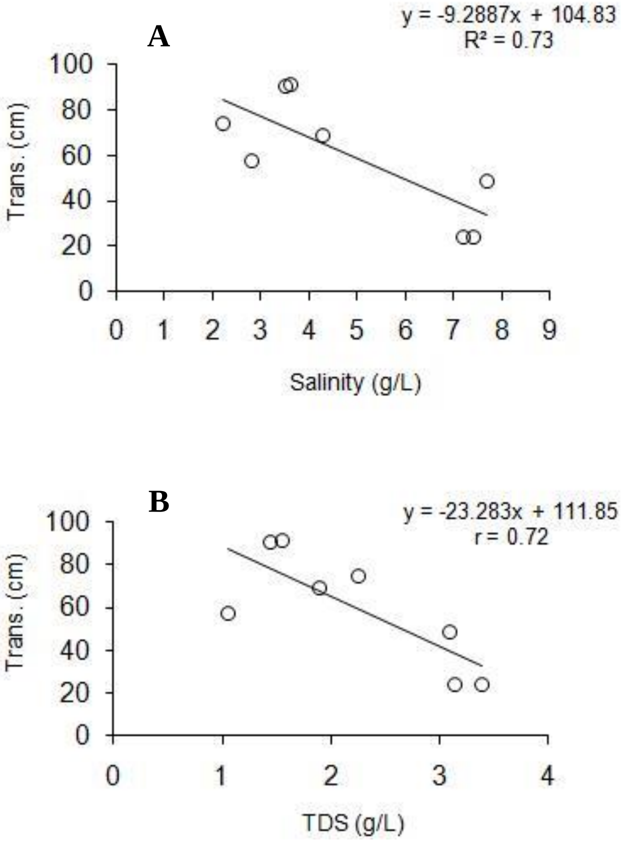

Figure 4. Regression analysis for the correlation between transparency against salinity (A) and TDS.

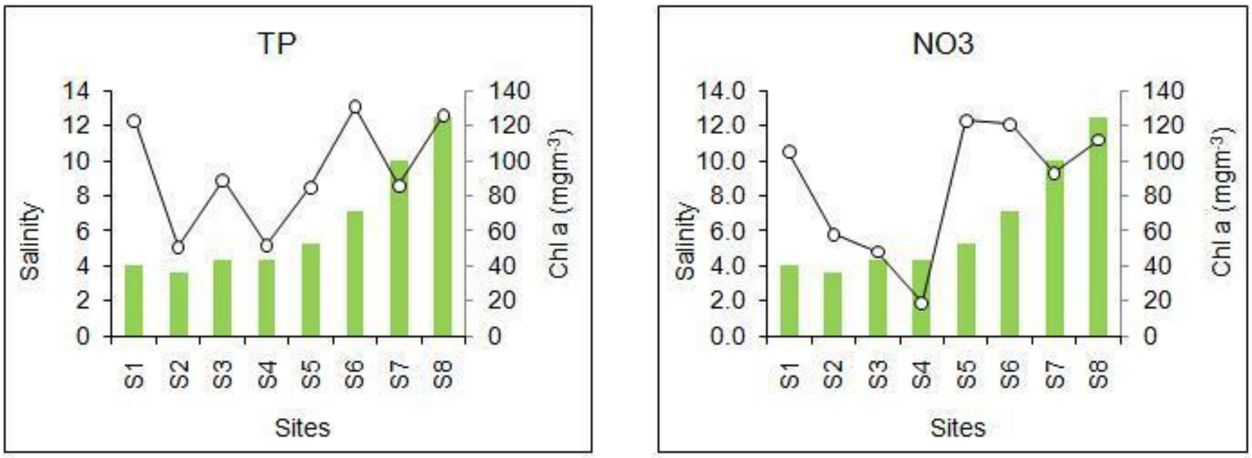

Figure 5. *In-Situ* values of Total phosphorous (TP; mg L^{-1}) and Nitrates (NO3; mg L^{-1}) against Chl a values (mgm^{-3}) in Lake Manzala on 4th March 2007.

4.2. Chlorophyll a dynamics

Chlorophyll *a* is a universal indicator of phytoplankton and showed wide variations on the sampling date throughout the eight sampling sites with a mean concentration of about 62.65 mgm^{-3}. Lower Chl *a* levels (flurometrically measured) were measured in the northern strip of the lake at sites 1, 2, 3 (Figures 2, 3 and Table 1). This low level of Chl *a* concentrations at these sites is attributed to the regular tidal flushing of the Mediterranean seawater via Boghaz El-Gamil inlet; however, higher levels were recorded in other locations along the lake. The maximum concentrations of Chl *a* recorded were 101.1 mgm^{-3} and 125 mgm^{-3}, at sites 7 and 8 respectively (Figure 2, 3 and Table 1). Both sites receive significant amount of wastes. Site 7, in the western corner, receives high amount of agricultural and sanitary wastes via El Serw Drain. On the other hand, site 8 in the south-eastern corner receives mixed amount of sanitary, agricultural and industrial wastes from Bahr Hadous and Bahr El-Bakar drains.

Two types of linear regression models were established; the first is a single band ratio and the second is a logarithmic band ratio, which derived from flurometrically measurements of Chl *a* values and satellite albedo (Chang *et al.,* 2004). The scatter plot (Figure 6) shows both types of regressions (left is the single band ratio and the right is the logarithmic band ratio).

Table 1. The average concentrations of Chl *a* and the corresponding reflected albedo

Station	Measured Chl *a* Average values (mgm^{-3})	Satellite Albedo		
		Band1	Band2	Band3
S1	30.5	0.173	0.081	0.101
S2	33	0.189	0.088	0.121
S3	43.1	0.197	0.091	0.092
S4	44.3	0.212	0.105	0.084
S5	53.3	0.213	0.112	0.071
S6	70.9	0.239	0.126	0.088
S7	125	0.267	0.122	0.079
S8	101.1	0.243	0.113	0.066

This approach is based on the correlation between the reflection and absorption of Chl *a* in the visible spectrum bands. Both regression types show different correlation, the least correlation was the single band ratio between ETM+1 and ETM+2 ($R^2 = 0.03$) as well as the log band ratio for the same two bands ($R^2 = 0.02$). However, ETM+1 (blue range of the visible light) and ETM+3 (red range of the visible light) show a significant absorption which increases with the increase of Chl *a* values (Figure 6). This probably explains that the rate of decrease in ETM+3 is faster than the decreasing rate in ETM+1. This could be interpreted due to the possible contribution of inorganic suspended sediments and dissolved organic matter to the reflection and absorption of the visible spectrum. The ratio of ETM+1 and ETM+3 might work more effectively in estimating Chl *a* when the Chl *a* concentration is above a certain level (35 mgm^{-3}) and the water is not much turbid. Comparing the single ratio with the logarithmic ratio, the later shows that the ratio between Log ETM+1 and Log ETM+3 produce good correlation with R^2 0.70.

A Chl *a* concentration map (Figure 7) was then generated by using the simulation of the single regression model. The map shows the spatial distribution pattern of Chl *a* in lake Manzala on the sampling day, which reflects the environmental conditions of the lake. The map shows steady low pattern of Chl *a* in the northern strip, however some higher values (red color) appears close to El-Ratma fish farm. This may be attributed to the flourishing of the phytoplankton due to high level of organic matter resulted from fish deeding residue.

On the other hand, medium and high levels of Chl *a* in other parts of the lake is attributed to the degree of discharge of pesticides and/or wastes together with the characteristics of the water basins. As shown in Figure (6) Lake Manzala has changed from an open water body to semi-closed basins, which in due course has a direct impact on the water quality. The size of the basin and the water circulation together with its physico-chemical properties, which play a significant role in the flourishing of phytoplankton. The smaller the size of the basin and less of water circulation together with convenient environment of low salinity, high temperature and higher organic matter help in flourishing the Chl *a* (e.g. south western and south eastern corner). Indeed, this reflects the environmental conditions of Lake Manzala and how much the changes in the morphology of the lake has contributed to the changes in the water quality.

However, the model was representing a single snapshot of the Chl a concentration in Lake Manzala, it was validated against further measurements of Chl a from another extra sampling locations giving high correlation at $R^2 = 0.95$.

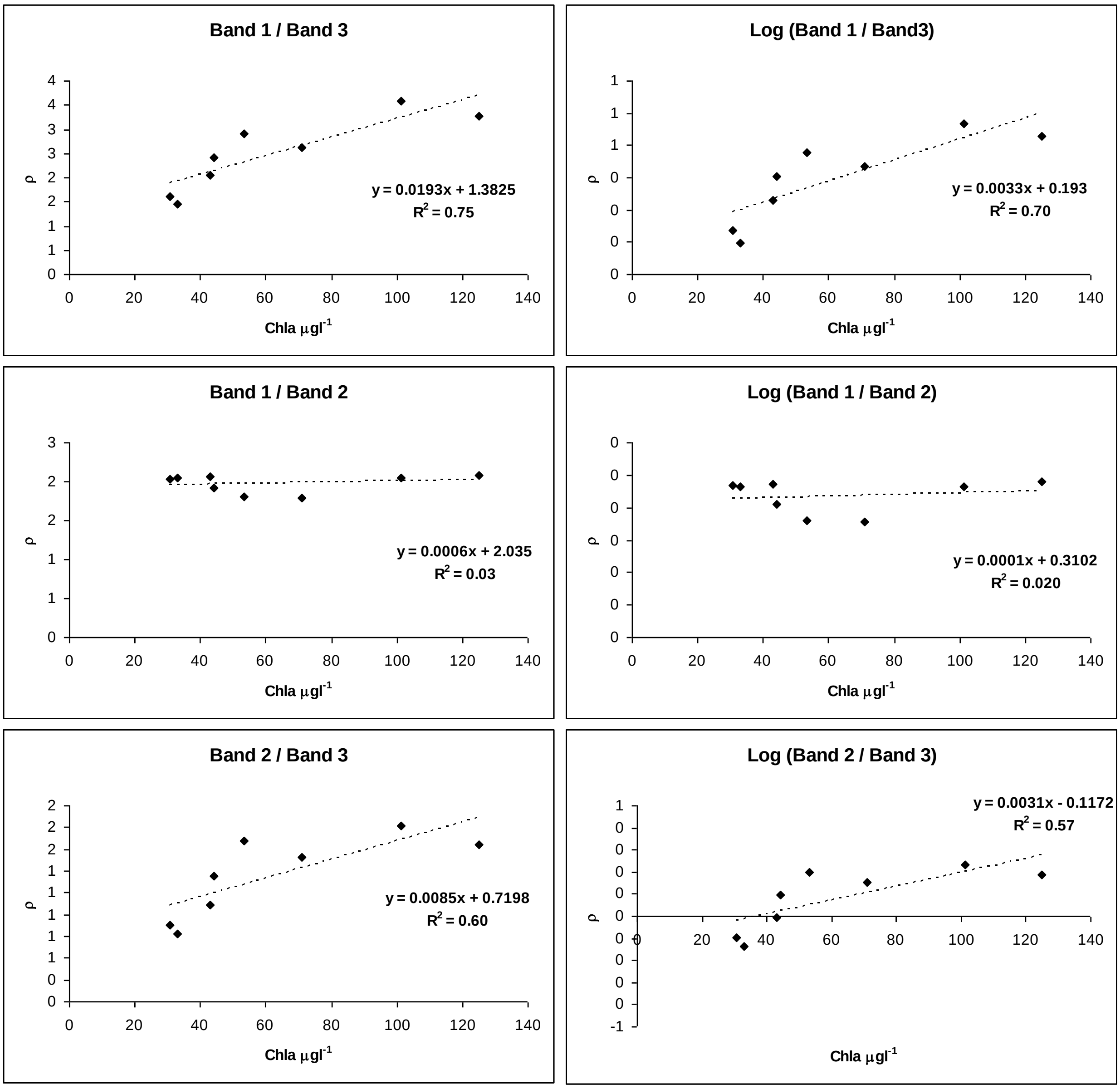

Figure 6. Single and Logarithmic band ratio regression models between *in-situ* Chl *a* data and satellite image reflection

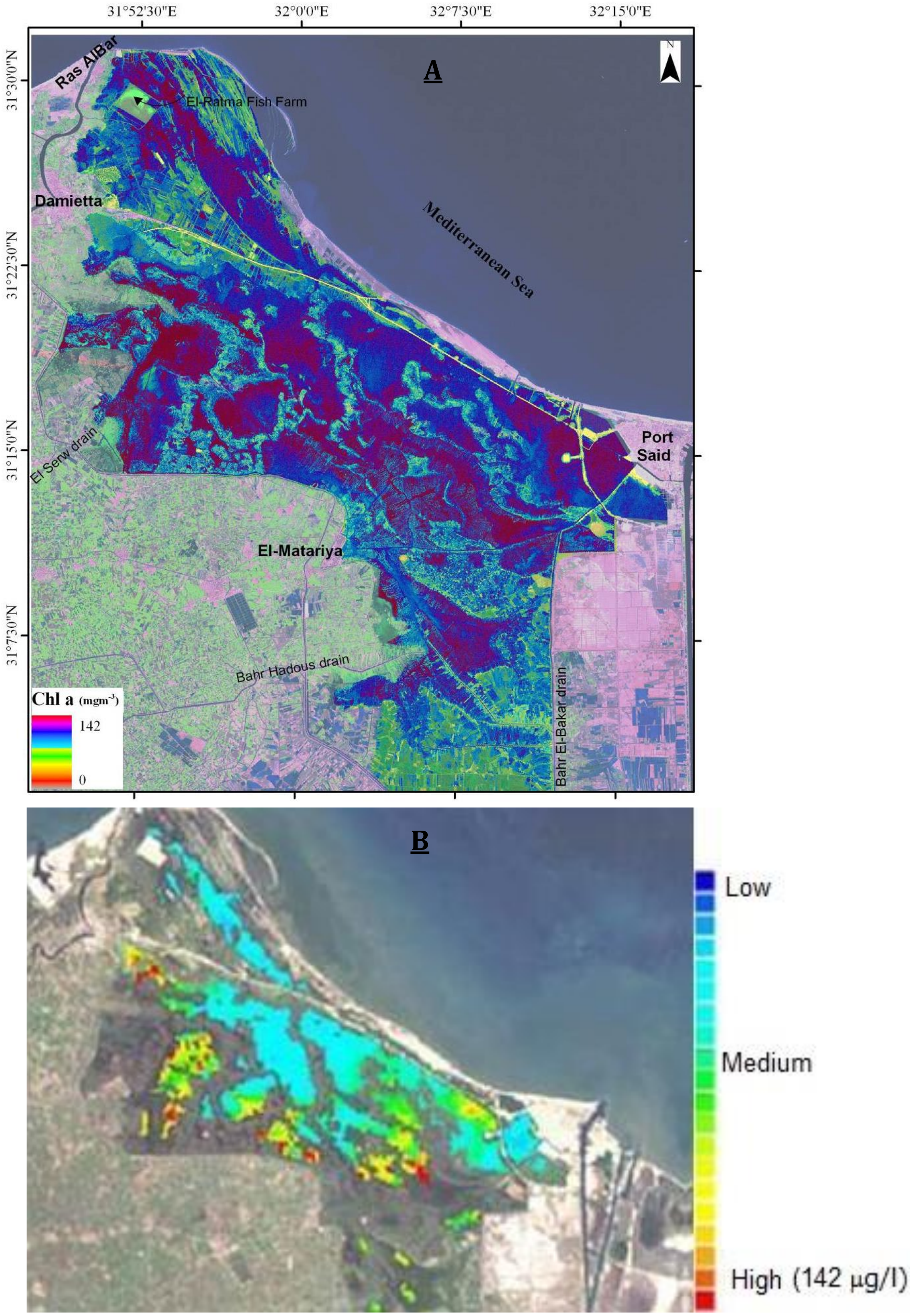

Figure 7. Spatial distribution map of chlorophyll-a of Lake Manzala (A = First run of the correlation model, B= refined and final result of the model)

5. Conclusions

Earth observations could offer an effective technique to monitor the rapid environmental changes of in-land lakes. Specific processing of landsate satellite image may play a significant role in mapping the costal lake's water quality in general and Chl *a* in particular. The ratio of ETM+1 / ETM+3 and Logarithmic of ETM+1 / ETM+3 show high correlation with Chl *a* concentration. This regression model showed a realistic estimate and simulated map of the chlorophyll-*a* concentration in the surface water and the little top water column due to the visible light penetrates the water column. There are, however, some limitations which could be tackled and therefore improve the results. Among these, the method is applied once with limited number of sampling locations, which does need more sampling locations for more confidence with the correlation.

The environmental conditions of Lake Manzala is highly dynamic coastal lake where it is not an open water body that might help easily predicting the distribution of Chl *a*. For more precise results this regression model needs to be applied on other coastal lakes in Egypt to assess its applicability and reliability. Moreover, further research is required to assess the feasibility of using such model to recognize the toxic algae in coastal water bodies, if present. It is highly recommended to re-apply the model on other similar environments with multiple satellite images and sampling locations.

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تقدير ورسم تركيزات الكلوروفيل كأحد المتغيرات البيئية في بحيرة المنزلة – مصر- باستخدام صور الأقمار الصناعية لاندسات 7

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تهدف هذه الدراسة إلى بناء نموذج آلي رقمي لتقدير ورسم قيم تركيزات صبغ الكلوروفيل كأحد المتغيرات البيئية التي تواجها البحيرات المصرية بصفة عامة و في بحيرة المنزلة بصفة خاصة باعتبارها واحدة من كبرى البحيرات الساحلية بمصر. اعتمدت الدراسة علي استخدام صور الأقمار الصناعية من النوع لاندسات 7. اعتمدت هذه الطريقة على إنشاء النسب الإحصائية بين قيم الكلوروفيل الفعلية (المقاسة من عينات المياه المجمعة في نفس توقيت صورة القمر الصناعي والتي تم تحليلها في المعمل) والانعكاسات الطيفية للمياه في الضوء المرئي. مبدئيا تم تصححيح صورة القمر الصناعي جغرافيا (هندسيا) وطيفيا (راديومتريا) ثم تم تحويل قيم الانعكاسات الطيفية الى ايريديانس.

تم إجراء علاقات إحصائية لإختبار القيم المقاسة مع علاقات نسبية مختلفة بين أطياف الضوء المرئي للقنوات 3،2،1 مع القياسات المعملية للكلوروفيل ا. وجدت العلاقة بين القناة رقم 1 (الضوء الأزرق من الضوء المرئي) والقناة رقم 3 (الضوء الأحمر من الضوء المرئي) هي أقوى العلاقات النسبية لتقدير قيمة تركيز الكلوروفيل ا مكونة علاقة خطية بنسبة 0.75 R^2. تم استخدام هذه العلاقة لتقدير توزيع تركيزات الكلوروفيل على البحيرة كاملة وقد تم التحقق من هذه النتائج مع مواقع أخرى لتحليل المياه والتي كونت علاقة خطية قوية بمعدل 0.95 R^2.

ناقش البحث كذلك العوامل البيئية المؤثرة والمسببة لارتفاع قيم الكلوروفيل ا في أجزاء من البحيرة وعلاقتها بالعوامل الفيزيوكيميائية للمياه بالبحيرة.