

Integrated Field Study, Remote Sensing and GIS Approach for Assessing and Monitoring Some Chemical Water Quality Parameters in Bardawil Lagoon, Egypt

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ABSTRACT: The purpose of this study was to use *in situ* water measurements combined with Landsat-8 Operational Land Imager (OLI) data and ancillary data in a geographic information system (GIS) as a tool in deriving water quality indicators of Bardawil Lagoon for sustainable management. The image acquisition dates were selected to be cloud-free and to be as close as possible to water sampling campaigns (24 March 2014, 28 June 2014, 16 September 2014 and 5 December 2014). The water quality of interest included, salinity (‰), pH and dissolved oxygen (mg/l). Reflectance values of OLI bands (B1, B2, B3, B4, B5, B6 and B7) and band ratios (B2/B3, B2/B4, B3/B1, B3/B2, B3/B4, B4/B1, B4/B2, B4/B3, B5/B7, B6/B5, B6/B7, B7/B5 and B7/B6) were compared with *in situ* measurements of water samples. Correlation and stepwise regression models were developed for each of the water quality parameter (WQP) measurements and the reflectance of image data. The results demonstrated that most of WQPs were significantly correlated well with OLI reflectance data ($R > 0.50$). Stepwise multiple linear regression models ($P \leq 0.05$) were used to quantify water quality dynamics and to prepare digital cartographic maps depicting the spatial distribution of water quality over the entire study area for each date. The efficiency of the proposed algorithms was investigated based on the values of bias and root-mean-square error. Results of this study on applicability of Landsat-8 coupled with GIS for retrieval of water quality indicators are promising.

KEYWORDS: Water quality parameters – Landsat-8 OLI – Correlation – Multiple regression models – Water Quality Maps – Bardawil Lagoon.

I. INTRODUCTION

Water quality (WQ) indicates the physicochemical and biological water characteristics. The presence of wastes, heavy metals and suspended solids in water results in its contamination. Identifying temporal changes in water quality across surface waters is troublesome via traditional techniques [1].

Traditional field measurements for monitoring water quality and other environmental parameters are expensive, time-consuming, require specialized trained personnel and both on site and laboratory analysis. Field measurements offer accurate readings for a point in site and time, however, lack the spatiotemporal view of water quality required for precise appraisal or management on a regional scale [2]. There are some restrictions in providing a synoptic spatiotemporal view of water quality [3]. Accordingly, it is necessary to monitor and assess the spatiotemporal distribution of WQPs to achieve a synoptic view of water bodies.

Recently, low cost associated with satellite data and ability to cover large and remote areas in all seasons with high spectral and spatial resolution enabled remote sensing techniques to be widely used in monitoring water quality [4, 5].

II. RELATED WORK

[6, 7, 5] showed that reliable empirical relationships can be obtained between Landsat reflectance values and *in situ* measurements of water quality.

To understand the relationship between field data and spectral reflectance values, statistical analysis had been widely utilized [8]. For instance, in studying the relationship between WQPs and Landsat 5 TM (bands 1 to 4) reflectance values, correlation analysis was used by [9]. [10] studied the correlation between the water quality index of surface water and Landsat 7 ETM⁺ (bands 1 and 2). These studies used various spectral bands (single band, band ratio, and band combinations) as the independent variable in regression equations to predict water parameters.

Despite the great importance of Bardawil Lagoon, monitoring studies using remote sensing technology coupled with geographical information system are still few. All studies dealt with traditional routine techniques in studying physicochemical properties of the lagoon [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. None had monitored water quality parameters in a synoptic view. It is worth mentioning that this study is the first to monitor and quantify Bardawil Lagoon's water quality using Landsat-8 imagery.

The current study aimed to use *in situ* water measurements combined with Landsat-8 Operational Land Imager (OLI) data and auxiliary data in a geographic information system (GIS) as a tool in deriving water quality indicators of Bardawil Lagoon for sustainable management.

III. MATERIAL AND METHODS

2.1. Study area:

Bardawil Lagoon (Fig.1) is a shallow natural tectonic hypersaline lagoon located on the northern coast of the Sinai Peninsula, Egypt, from a point about 45 Km East of Port Said and extending to about 20 Km West of El-Arish at latitude 31°03' -31°15' N and longitude 32°40' -33°32' E. The lagoon extends for about 80 km length with a maximal width of 18 km and is separated from the Mediterranean Sea by a long arc-shaped sand barrier of about 90 km length, with a maximum width of 2 km. The mean water depth inside the lagoon is around 1.21 m [17]. Seawater enter the lagoon through three inlets; the western Boughaz I, the middle eastern Boughaz II and the natural eastern Boughaz El-Zaranik. The lagoon's area changed from 600 km² during 1991 [21] to 518.99 km² during 2004 [17]. Among the Mediterranean coastal lagoons, Bardawil is the second largest lagoon after El-Manzala in surface area [22]. Recently; Ramsar listed Bardawil as one of four sites in Egypt designated as Wetlands of International Importance.

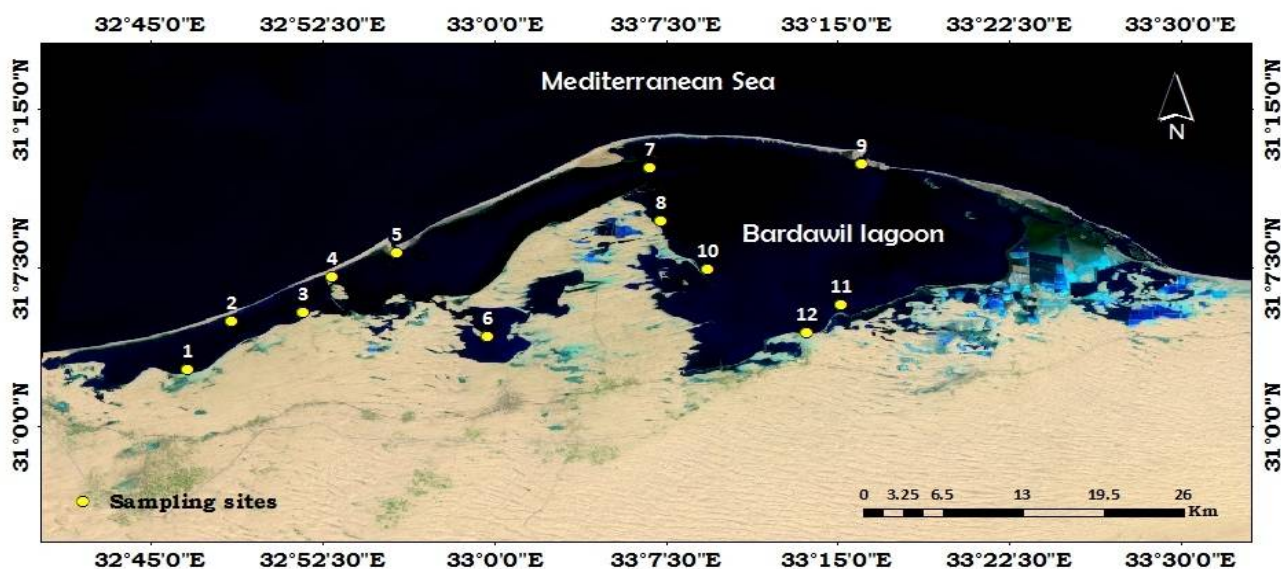


Fig. (1): Sampling sites of Bardawil Lagoon. False colour composite of Landsat-8 image (RGB = 753).

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

2.2. Water quality sampling:

Twelve sampling sites covering the entire study area were selected to measure different WQPs during March, June, September and December 2014 in Bardawil Lagoon (Fig. 1). Global positioning system (Garmin GPS) was used to detect the X and Y coordinates of each site location in the field (Table 1). GPS data were georeferenced to the Universal Transverse Mercator system (UTM/zone 36-N using spheroid/datum WGS-84) to make them compatible with the Landsat data.

Field Hydrolab was used to measure salinity, pH and dissolved oxygen directly in the field. Hydrolab's probe was hanged in water whilst the measurements were taken directly from a small screen on the boat.

Table (1): Location of sampling sites in Bardawil Lagoon.

Site		Location	
Name	Number	Longitude	Latitude
Rabba	1	32° 46' 33.96"	31° 2' 40.56"
Nigela	2	32° 48' 29.52"	31° 4' 58.8"
El Naser	3	32° 51' 38.88"	31° 5' 23.64"
Rumia	4	32° 52' 54.12"	31° 7' 3.36"
Boughaz #1	5	32° 55' 41.88"	31° 8' 13.2"
El Rewak	6	32° 59' 41.64"	31° 4' 13.8"
El Kalss	7	33° 6' 45"	31° 12' 13.68"
Mateblis	8	33° 7' 13.8"	31° 9' 44.28"
Boughaz #2	9	33° 16' 3.72"	31° 12' 26.28"
Mazfek	10	33° 9' 19.08"	31° 7' 25.32"
Karn Hamd	11	33° 15' 6.84"	31° 5' 45.24"
El-Tolol	12	33° 13' 38.64"	31° 4' 25.68"

2.3. Satellite Data:

In the current study, a total of four cloud-free Landsat-8 OLI_TIRS scenes dated 24 March 2014, 28 June 2014, 16 September 2014 and 5 December 2014 (Path: 175/ Row: 39) were downloaded as a zipped file at no cost from the United States Geological Survey (USGS) for the analysis. The image acquisition dates were selected to be as close to water sampling campaigns as possible. All selected Landsat scenes were processed to a standard level-1 precision terrain corrected (L1T) product. The downloaded scenes were processed in ENVI software to stack the OLI bands together. A subarea of 7641 by 7791 pixels covering the study area was extracted. On the subset images, the raw digital numbers were converted to reflectance using raster calculator in ArcMap 10.1.

2.4. Band Rationing:

Rationing is an enhancement process in which the reflectance values of one band were divided by that of any other band in the sensor array. Band ratios used in this study were B2/B3, B2/B4, B3/B1, B3/B2, B3/B4, B4/B1, B4/B2, B4/B3, B5/B7, B6/B5, B6/B7, B7/B5 and B7/B6.

2.5. Development of regression models for estimating water quality parameters from satellite data:

Microsoft Excel 2013 software was utilized to perform the statistical analysis. Correlation matrices were produced for OLI bands (B1, B2, B3, B4, B5, B6 and B7), band ratios (B2/B3, B2/B4, B3/B1, B3/B2, B3/B4, B4/B1, B4/B2, B4/B3, B5/B7, B6/B5, B6/B7, B7/B5 and B7/B6) and WQPs. Pearson's correlation coefficient (R) was estimated in each combination of independent variables (Landsat-8 OLI reflectance data) with dependent ones (measured WQPs) for each scene. Only those independent variables combination having highest R-value ($R \geq 0.50$) with dependent variables were selected for the equation and model to estimate WQPs.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Multiple Linear regression (MLR) models were used to predict the WQPs from Landsat-8 OLI reflectance data. The general formula for multiple regressions is as follows:

$$\text{WQP} = a + b_1X_1 + b_2X_2 + \dots + \varepsilon$$

Where;

WQP = predicted water quality parameter.

X's = reflectance variables acquired from the Landsat 8 OLI images.

a = intercept.

b₁, b₂, etc. = regression coefficients.

ε = Model error

Independent variables were chosen to be highly significant (P<0.05). Coefficient of determination (R²), adjusted R square, standard error (±SE) and significance F-ratio values were considered in the regression equation. Bias and root mean square error (RMSE) were conducted to describe statistical errors.

2.6. Application of the regression models to the study area:

For GIS analysis, Bardawil Lagoon's boundary was digitized at 1:50,000 scale using the polygon shapefile in ArcGIS 10.1 software. The MLR models, developed between the WQPs and the reflectance values of Landsat-8 OLI bands for 12 sample sites, were extended to each pixel in the entire study area for mapping the WQPs for each date using ArcMap.

IV. RESULTS AND DISCUSSION

3.1. Descriptive statistics of field measurements:

Salinity (‰):

Boughaz I and Boughaz II represented the conjugation points of Mediterranean Sea with Bardawil Lagoon for seawater exchange. These points recorded the minimum values of water salinity (Table 2). The maximum values of salinity were recorded at station 1 (western arm) especially during June (64.1‰). The means of water salinity fluctuated between 48.46, 51.03, 51.86 and 51.60‰ in March, June, September and December 2014, respectively. Overall, March recorded the minimum values of salinity in most of the stations in Bardawil Lagoon.

During the Israeli occupation of Sinai, the two artificial inlets were closed due to progressive silting resulting in a drastic increase in the lagoon's salinity reaching up to 70–90‰ [23]. In 1970, the salinity reached 170‰ at the southern part of the lagoon [24]. However, in 1971, dredging took place and the salinities decreased. Accordingly, dredging was carried out continuously to preserve the biological equilibrium in the lagoon [25]. During the period from 1997 – 2014, salinity values ranged from 36.9‰ during 2011 [26] to 74.5‰ during 2004 [15].

pH:

Water of Bardawil Lagoon is always alkaline throughout the year with obvious slight variations among different stations and months (Table 2). Results showed that pH values ranged from 7.4 at El-Tolol station (December 2014) to 8.6 at Mateblis station (September 2014). [19] attributed the decrease in pH at El-Tolol station to its location near the housing, lack of seawater exchange and to the accumulation of organic wastes coming out of the boats.

In the present study, pH increased slightly during March due to removal of carbon dioxide from water by large amounts of seagrasses during photosynthesis. Whereas, the decrease in pH values during June and September was due to bacterial fermentation and decomposition of organic matter. The average readings of water pH were 8.58, 8.13, 8.33 and 8.03 in March, June, September and December 2014, respectively.

The year 1997, recorded the lowest pH value in Bardawil Lagoon (pH=7) [13], whereas the highest one was during 2012 with a value of 9.01 [27].

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Dissolved Oxygen (mg/l):

Bardawil Lagoon was well oxygenated during different time intervals (Table 2). In terms of locations, station "5" (Boughaz I) and station "9" (Boughaz II) recorded the highest concentration of dissolved oxygen in the current study. This could be due to the increases in rate of seawater exchange at these points [19].

Dissolved oxygen values ranged from 4.5 mg/l (September 2014) to 6.7 mg/l (March 2014), in the present study. Similarly, [19] found that the lowest and highest values of dissolved oxygen were recorded in August and February, respectively.

The mean values of DO were 5.73, 5.49, 5.54 and 5.61 mg/l in March, June, September and December 2014, respectively (Table 2). Inferring that cold water (in December and March) can hold more dissolved oxygen than warm water (in June and September).

Table (2): WQPs measured in sampling sites at Bardawil Lagoon during 2014.

Station No.	Salinity (‰)				pH				DO (mg/l)			
	Mar.	Jun.	Sep.	Dec.	Mar.	Jun.	Sep.	Dec.	Mar.	Jun.	Sep.	Dec.
1	55.5	64.1	64	63.1	8.8	8.2	8.5	8.1	5.2	5.3	4.5	4.6
2	52	59.9	58.4	59.2	8.7	8.1	8.4	8.1	5.2	5.7	5.1	4.7
3	50.2	53.1	55.6	54.2	8.4	8.1	8.4	8.1	6.1	5.9	5.4	5.3
4	46.7	43.4	44.7	47.1	8.8	8	8.2	8.3	6.3	6.1	5.9	6.1
5	39.8	39.2	40.1	41.1	8.7	8.1	8.1	8.2	6.7	6.3	6.1	6.3
6	49.4	51.2	51.4	51.2	8.6	8	8.3	7.9	4.9	4.9	4.9	4.9
7	41.8	49.4	46.5	43.6	8.8	8.2	8.3	8.1	6	5.8	6.1	6.1
8	49.1	51.3	51.2	49.8	8.1	8	8.6	8.2	5.8	5.1	5.4	5.9
9	41.2	38.9	40.5	40.2	8.5	8.1	8.2	7.6	6.6	6.1	6.3	6.5
10	51.3	57.1	58.1	57.1	8.4	8.3	8.3	8.2	4.9	4.7	5.2	5.7
11	54.1	50.2	55.4	55.9	8.8	8.3	8.4	8.1	5.4	5.1	5.9	5.8
12	50.4	54.5	56.4	56.7	8.4	8.1	8.3	7.4	5.7	4.9	5.7	5.4
Min.	39.8	38.9	40.1	40.2	8.1	8	8.1	7.4	4.9	4.7	4.5	4.6
Max.	55.5	64.1	64	63.1	8.8	8.3	8.6	8.3	6.7	6.3	6.3	6.5
Mean	48.46	51.03	51.86	51.60	8.58	8.13	8.33	8.03	5.73	5.49	5.54	5.61
± SE	1.46	2.22	2.17	2.13	0.06	0.03	0.04	0.08	0.18	0.16	0.15	0.18

3.2. Correlation analysis:

The correlation matrices between the measured WQPs and the reflectance values of Landsat-8 OLI bands for March, June, September and December 2014 were shown in Table (3).

Salinity:

In the present study, salinity was highly positively correlated with B4/B2 (R=0.830) in March 2014, (R=0.733) in June 2014, (R=0.754) in September 2014 and (R=0.697) in December 2014.

pH:

Correlation analysis between pH and reflectance values in March 2014 was below 0.30 and P>0.05 therefore, it was excluded from regression analysis. pH was positively correlated with B5/B7 (R=0.670) in June 2014, with B4/B3 (R=0.601) in September 2014 and with B6/B7 (R=0.567) in December 2014.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Dissolved oxygen:

B2/B4 showed positive correlation with dissolved oxygen in the four dates especially in March 2014 (R=0.75) and September 2014 (R=0.57). However, B2/B3 was highly correlated with dissolved oxygen than B2/B4 in June 2014 (R=0.624) and in December 2014 (R=0.819).

Table (3): Correlation matrix of OLI bands and WQPs through Pearson's correlation equation for Bardawil Lagoon during Mar., Jun., Sept. and Dec. 2014.

	March 2014			June 2014			September 2014			December 2014		
	S	pH	DO	S	pH	DO	S	pH	DO	S	pH	DO
S	1			1			1			1		
pH	-0.044	1		0.326	1		0.688	1		0.029	1	
DO	-0.786	0.011	1	-0.611	-0.292	1	-0.800	-0.597	1	-0.837	0.026	1
B1	0.280	0.169	-0.138	0.134	-0.067	-0.105	-0.021	-0.347	-0.035	0.033	-0.269	-0.397
B2	0.373	0.139	-0.266	0.269	0.046	-0.221	0.076	-0.302	-0.061	0.105	-0.355	-0.471
B3	0.587	0.126	-0.507	0.525	0.108	-0.427	0.373	-0.014	-0.310	0.414	-0.268	-0.707
B4	0.695	0.023	-0.580	0.616	0.030	-0.468	0.552	0.235	-0.396	0.555	-0.098	-0.740
B5	0.464	-0.117	-0.249	0.254	-0.361	-0.131	0.350	0.146	-0.269	0.384	-0.351	-0.537
B6	0.391	-0.090	-0.192	0.226	-0.387	-0.100	0.315	0.134	-0.265	0.271	-0.480	-0.382
B7	0.339	-0.094	-0.136	0.199	-0.436	-0.030	0.294	0.119	-0.258	0.200	-0.523	-0.328
B2/B3	-0.784	-0.114	0.741	-0.722	-0.175	0.624	-0.596	-0.238	0.499	-0.636	0.190	0.820
B2/B4	-0.862	0.091	0.754	-0.732	-0.018	0.591	-0.776	-0.609	0.574	-0.707	-0.106	0.729
B3/B1	0.691	0.112	-0.645	0.624	0.177	-0.520	0.477	0.085	-0.378	0.528	-0.257	-0.769
B3/B2	0.768	0.115	-0.727	0.716	0.171	-0.601	0.601	0.240	-0.500	0.633	-0.180	-0.828
B3/B4	-0.771	0.259	0.616	-0.464	0.145	0.319	-0.416	-0.592	0.225	-0.484	-0.371	0.317
B4/B1	0.781	-0.026	-0.682	0.702	0.058	-0.545	0.660	0.383	-0.458	0.639	-0.042	-0.745
B4/B2	0.830	-0.068	-0.723	0.733	0.008	-0.572	0.754	0.585	-0.538	0.697	0.064	-0.733
B4/B3	0.752	-0.286	-0.592	0.431	-0.184	-0.305	0.378	0.601	-0.192	0.471	0.346	-0.299
B5/B7	-0.049	-0.007	-0.172	0.0004	0.670	-0.257	-0.161	-0.108	0.317	0.043	0.534	0.115
B6/B5	0.197	0.014	-0.009	0.109	-0.546	0.050	0.237	0.143	-0.312	0.075	-0.562	-0.153
B6/B7	0.437	0.081	-0.553	0.215	0.575	-0.610	0.090	0.064	0.152	0.361	0.567	-0.088
B7/B5	0.048	-0.003	0.150	0.029	-0.638	0.242	0.187	0.107	-0.290	-0.035	-0.609	-0.090
B7/B6	-0.462	-0.065	0.570	-0.187	-0.557	0.601	-0.096	-0.072	-0.146	-0.361	-0.588	0.093

3.3. Multiple Linear regression models:

The best fitting MLR models representing the statistical relationships between the measured WQPs and the corresponding reflectance values of Landsat images were shown in **Table (4)**. The models established in this study involved spectral ratios rather than single band. Multiple regression models with band ratio were found to be more powerful and more reliable than the regression model with single band [28].

Independent variables significantly and linearly related to the dependent variables (WQPs) were only involved in the models. All formulated models represented acceptable positive correlations ($R \geq 0.50$) among which seven coefficients were equal to or higher than 0.7. The significances of the regressive retrieval models ($P \leq 0.05$) indicated that there existed a statistical perfect correlation for WQPs including salinity, pH and dissolved oxygen to Landsat-8 OLI data. [29] stated that in estimating the relationship between satellite data and field observations, not all WQPs responded similarly to the statistical analysis.

Coefficient of determination (R^2) assessed the relative fitness of the regression model. The higher coefficient of determination revealed that the independent variables (i.e., spectral bands) were good predictors of the dependent variable (i.e., WQ parameter). It was found that the R^2 got larger as more variables were added. Consequently, incorporating more spectral information into the models enhanced the accuracy of the established model.

It is worth mentioning that in this study, the formulated models for salinity, pH and dissolved oxygen were specific for Bardawil Lagoon. [30] stated that in most cases the models developed are site-specific. [31] mentioned that the algorithms developed between reflectance and water quality for Green Bay, Lake Michigan, Wisconsin, United states, cannot be applied to Yellowstone and Jackson Lakes, Wyoming, United states, despite resemblance in the water quality–reflectance relationships.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Table (4): The regression equations of water quality parameters over Bardawil Lagoon in the present study.

WQP	Date	Model	R	R ²	Adjusted R ²	±SE	Significance F
Salinity (%)	24 Mar. 2014	Y = 19.874 + 49.433 * B4/B2	0.83	0.689	0.658	2.97	0.0008
	28 Jun. 2014	Y = 4.9301 + 79.237 * B4/B2	0.73	0.536	0.490	5.49	0.006
	16 Sep. 2014	Y = -78.033 - 267.767 * B3/B1 + 391.103 * B3/B2	0.81	0.650	0.572	4.92	0.008
	5 Dec. 2014	Y = -170.999 - 5272.41 * B4/B2 + 6555.56 * B4/B1 + 4146.53 * B3/B2 - 2517.83 * B4 - 4528.19 * B3/B1	0.96	0.931	0.872	2.63	0.002
pH	28 Jun. 2014	Y = 7.4885 + 0.28857 * B5/B7	0.66	0.448	0.393	0.08	0.017
	16 Sep. 2014	Y = 6.9879 + 2.05479 * B4/B3	0.60	0.361	0.297	0.11	0.038
	5 Dec. 2014	Y = 4.1490 + 2.65169 * B6/B7	0.56	0.321	0.253	0.23	0.054
DO (mg/l)	24 Mar. 2014	Y = 2.7749 + 1.67414 * B2/B4	0.75	0.568	0.525	0.43	0.004
	28 Jun. 2014	Y = - 8.6889 + 3.59084 * B2/B3 + 13.73666 * B7/B6	0.88	0.784	0.736	0.28	0.001
	16 Sep. 2014	Y = 2.2881 + 1.68452 * B2/B4	0.57	0.329	0.262	0.45	0.051
	5 Dec. 2014	Y = - 3.1377 + 6.51935 * B2/B3	0.81	0.671	0.639	0.37	0.001

3.4. Validation:

Because of changed water conditions, on-spot validation of the quantified results later on was not workable. A common practice is to collect field samples as sizeable as possible. A portion of them is utilized in constructing the empirical model while the rest is used as independent checkers to verify the results [32]. In the present study, the sample size for each WQP per trip was small (n = 12). Therefore, in order to overcome the restrictions associated with a small sample size, all the available samples were used in developing the empirical model and the validation was based on its goodness-of-fit [33].

The current results showed that all WQPs had satisfied retrieval results according to the root mean square error (RMSE), which was the most important criterion for fit if the main purpose of the model was prediction. It indicated how close the measured data points were to the model's predicted values.

Figs. (2 – 4) displayed the visual matching of the measured water variables against the predicted ones in Bardawil Lagoon for salinity, pH and dissolved oxygen, respectively. Tables (5 – 7) illustrated the R², ±SE, RMSE and Bias values computed for the regression between the measured and predicted WQPs mentioned before, respectively.

Salinity:

Concerning salinity, Table (5) showed that December 2014 recorded the highest coefficient of determination (R²=0.93). The observed and predicted results were almost the same in March and December 2014. However, in June and September 2014 the modelled results showed a smoother variation than the observed data (Fig. 2).

Table (5): Linear regression equations of measured and predicted values of salinity in Bardawil Lagoon during Mar., Jun., Sep. and Dec. 2014.

Predicted Salinity(‰) = a + b Measured Salinity(‰)							R ²	±SE	RMSE	Bias
Date	a	b								
		value	±SE	P value	95% C.I					
					Lower	Upper				
Mar. 2014	15.046	0.6895	±0.14	< 0.005	0.363	1.015	0.68	±2.47	2.7165	-0.0003
Jun 2014	23.639	0.5367	±0.15	< 0.05	0.185	0.888	0.53	±4.02	5.0149	-0.0001
Sep. 2014	18.145	0.6501	±0.15	< 0.005	0.314	0.986	0.65	±3.76	4.2663	0.0007
Dec. 2014	3.5782	0.9306	±0.08	< 0.005	0.751	1.109	0.93	±1.96	1.8617	0.0036

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(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

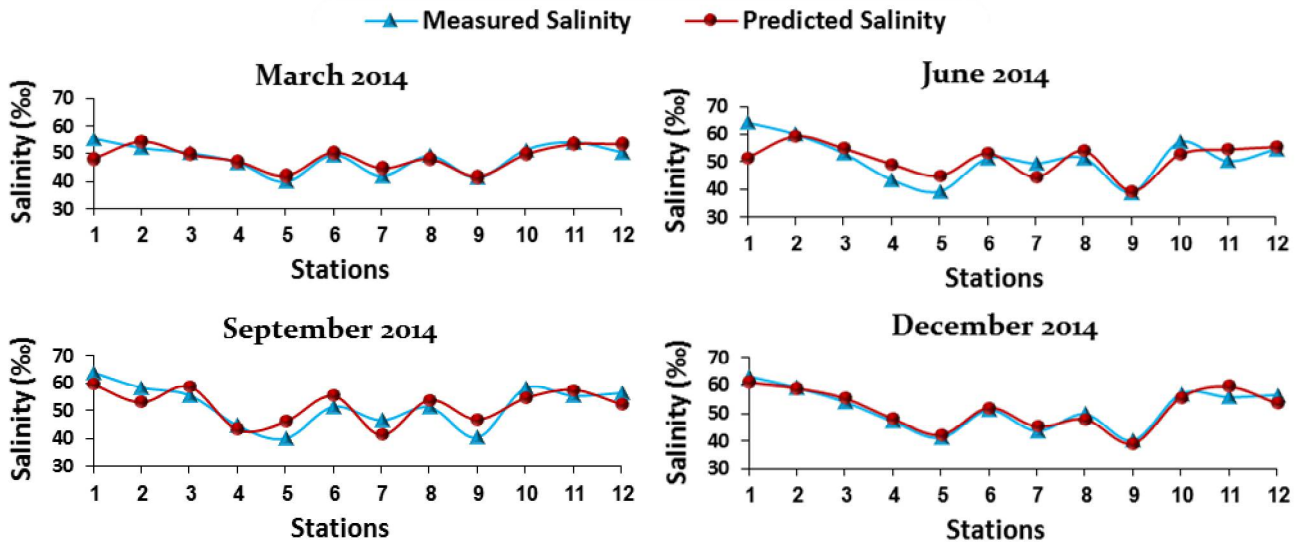


Fig. (2): Measured against predicted values of salinity in 12 stations at Bardawil Lagoon during March, June, September and December 2014.

pH:

Fig. (3) revealed that the predicted values of pH matched the observed ones especially in June 2014, although pH was classified as non-optical WQP. The values of coefficient of determination computed for the regression between measured and predicted pH were presented in Table (6). [29] developed an algorithm for estimating pH using spectral reflectance values of Worldview-2 satellite for the eastern side of Rosetta branch of the Nile Delta. They found that both field and calculated pH data showed a good agreement with $R^2=0.6$ indicating a good fitting.

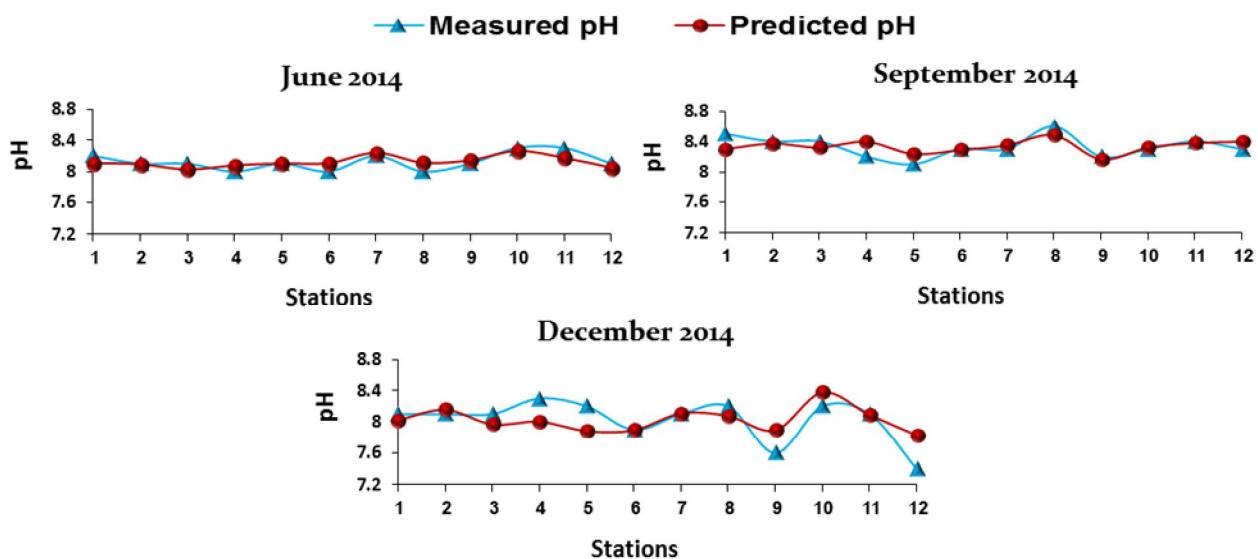


Fig. (3): Measured against predicted values of pH in 12 stations at Bardawil Lagoon during June, September and December 2014.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Table (6): Linear regression equations of measured and predicted values of pH in Bardawil Lagoon during June, September and December 2014.

Predicted pH = a + b Measured pH							R ²	±SE	RMSE	Bias
Date	a	b								
		value	±SE	P value	95% C.I					
					Lower	Upper				
Jun 2014	4.4801	0.4486	±0.15	0.01	0.098	0.799	0.45	±0.05	0.075	0.00002
Sep 2014	5.3246	0.361	±0.15	0.03	0.022	0.699	0.36	±0.06	0.105	0.00003
Dec 2014	5.4468	0.3213	±0.14	0.05	-0.007	0.650	0.32	±0.13	0.210	0.000001

Dissolved oxygen:

Both field and predicted data sets of dissolved oxygen showed a good agreement as seen in Fig (4), with the best fitting was in June 2014 (R²=0.78) (Table 7).

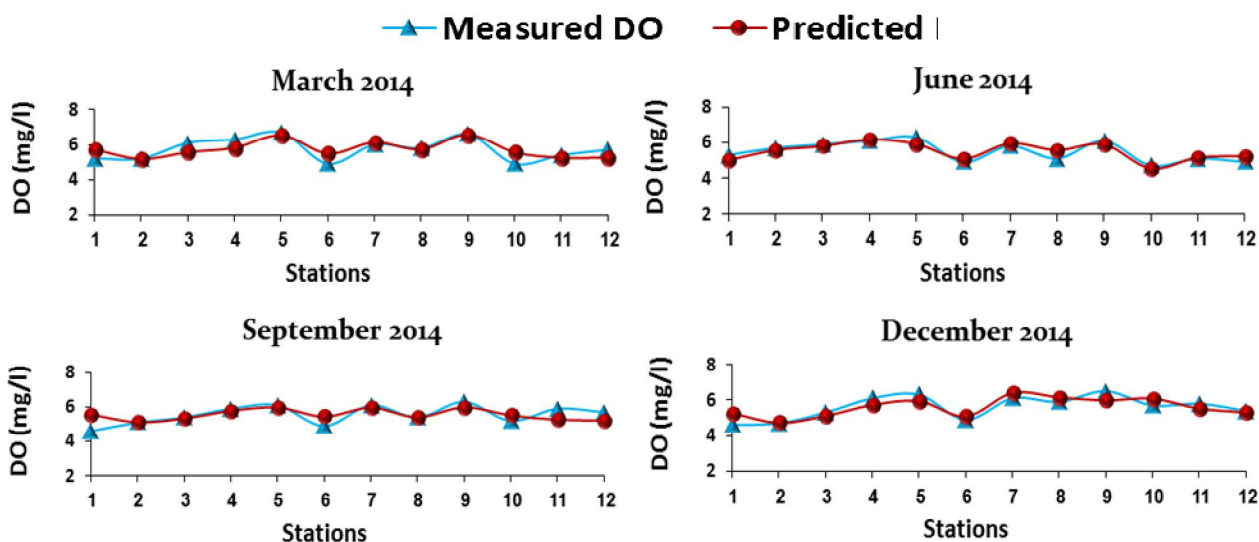


Fig. (4): Measured against predicted values of DO in 12 stations at Bardawil Lagoon during March, June, September and December 2014.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

Table (7): Linear regression equations of measured and predicted values of DO in Bardawil Lagoon during March, June, September and December 2014.

Predicted DO (mg/l) = a + b Measured DO (mg/l)							R ²	±SE	RMSE	Bias
Date	a	b								
		value	±SE	P value	95% C.I					
					Lower	Upper				
Mar. 2014	2.4732	0.5686	±0.15	0.004	0.219	0.917	0.57	±0.32	0.392	0.000071
Jun 2014	1.186	0.784	±0.13	0.0001	0.494	1.073	0.78	±0.23	0.246	-0.00002
Sep. 2014	3.7222	0.3293	±0.14	0.05	-0.001	0.660	0.33	±0.26	0.418	0.000097
Dec. 2014	1.8404	0.6719	±0.14	0.001	0.341	1.002	0.67	±0.31	0.345	-0.00008

3.5. Water quality interpolation:

Quantifying WQPs using remote sensing required transforming satellite image into water quality maps based on the empirical and semi-empirical relationships between the parameters and image data [34]. Accordingly, cartographic maps for the spatiotemporal distributions of salinity, pH and dissolved oxygen based on the retrieved models for Bardawil Lagoon were developed.

Salinity:

Fig. (5) depicted the spatiotemporal water salinity distributions inside the lagoon. Spatially, salinity near the inlets was lower than the rest of the lagoon, due to the continuous seawater exchange, and continued to increase towards the southern shore with the highest values recorded at western arm of the lagoon. [35] mentioned that the southern and western areas of Bardawil Lagoon recorded the highest salinities whereas near the inlets, salinity was the lowest. Temporally, salinity increased in September (70.11%). However, this increment was compensated by winter rain during December (39.1%). [13, 17] recorded similar observations.

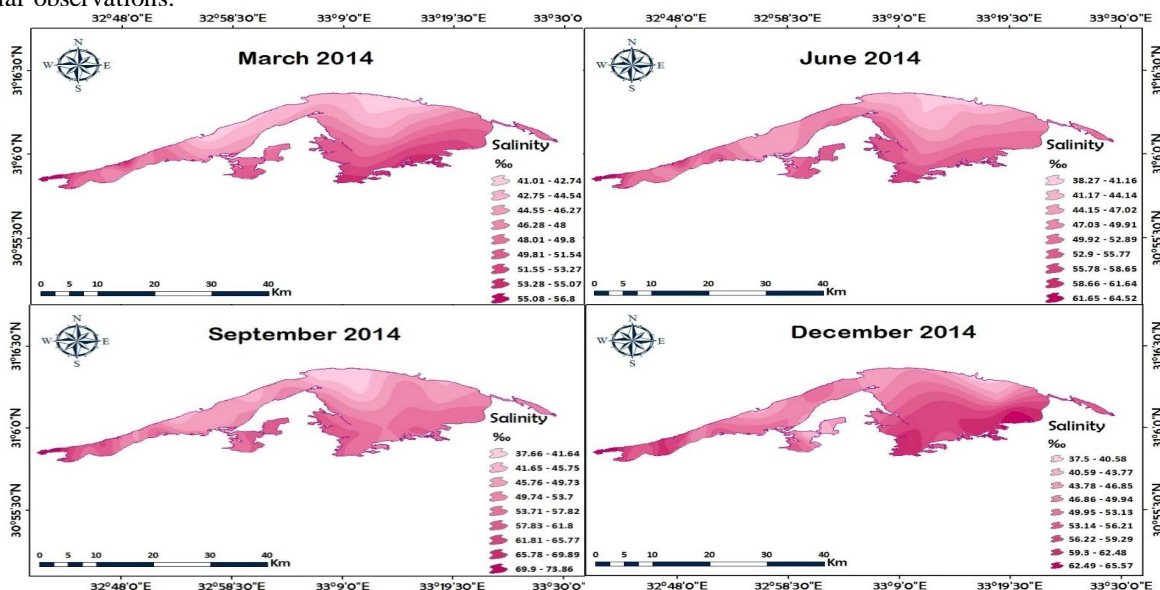


Fig. (5): Cartographic maps of salinity distribution as obtained from GIS analysis in Bardawil Lagoon during March, June, September and December 2014.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

pH:

The spatiotemporal distribution of pH inside Bardawil Lagoon was shown in Fig. (6). The pH spectrum of the lagoon was found to be alkaline ranging between 8.03 – 8.29 in June, 8.16 – 8.4 in September, and 7.68 – 8.53 in December 2014. According to [36], this range is optimal for aquatic organisms to complete their life cycle. pH values attained its peak in the middle and eastern area of the lagoon (in June 2014), shifted little to the left and to the southern shore (in September 2014) and was directed towards the north in December 2014 (Fig. 6). This could be attributed to the temporal variations in the growing seasons of aquatic plants dominating the lagoon. On the other hand, the area near the inlets recorded the lowest pH values throughout the year due to the continuous exchange with seawater (Fig. 6).

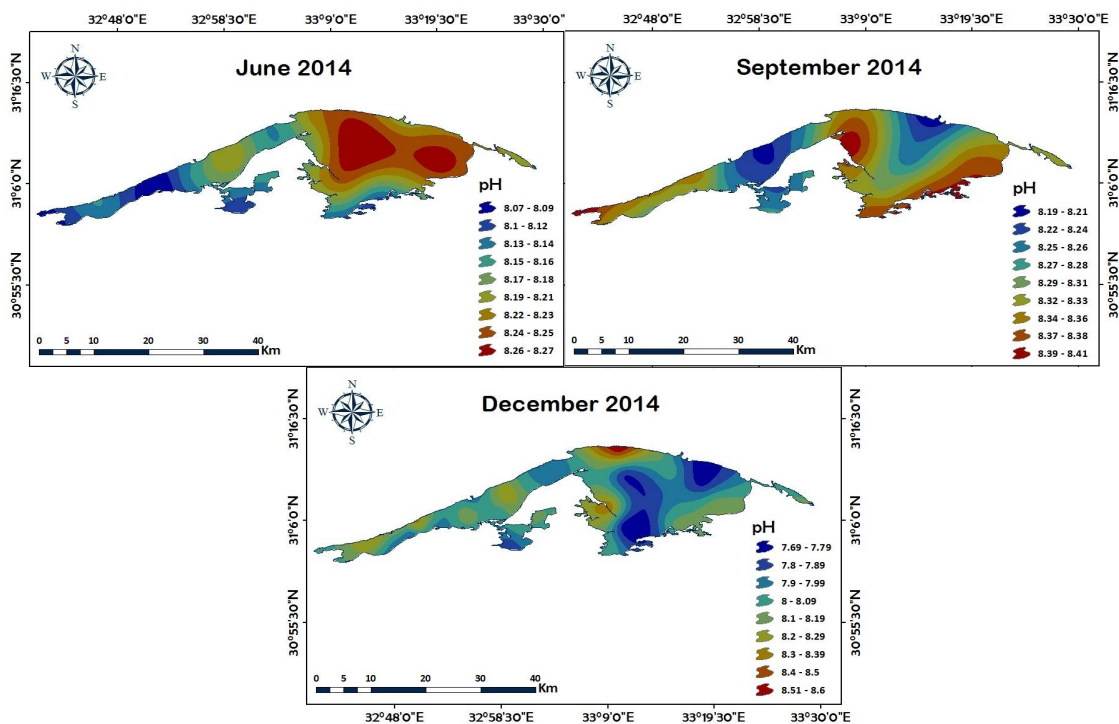


Fig. (6): Cartographic maps of pH distribution as obtained from GIS analysis in Bardawil Lagoon during June, September and December 2014.

Dissolved oxygen:

Fig. (7) presented the spatiotemporal distribution of dissolved oxygen inside Bardawil Lagoon. Dissolved oxygen can be used as index of lagoon's productivity. In the present study, the majority of the lagoon lied within the range 5 – 6.2 mg/l. According to [37], this range supports fish and vegetation health. Unlike salinity, dissolved oxygen concentrations near the inlets were higher than the rest of the lagoon and decreased towards the southern shore (Fig. 7).

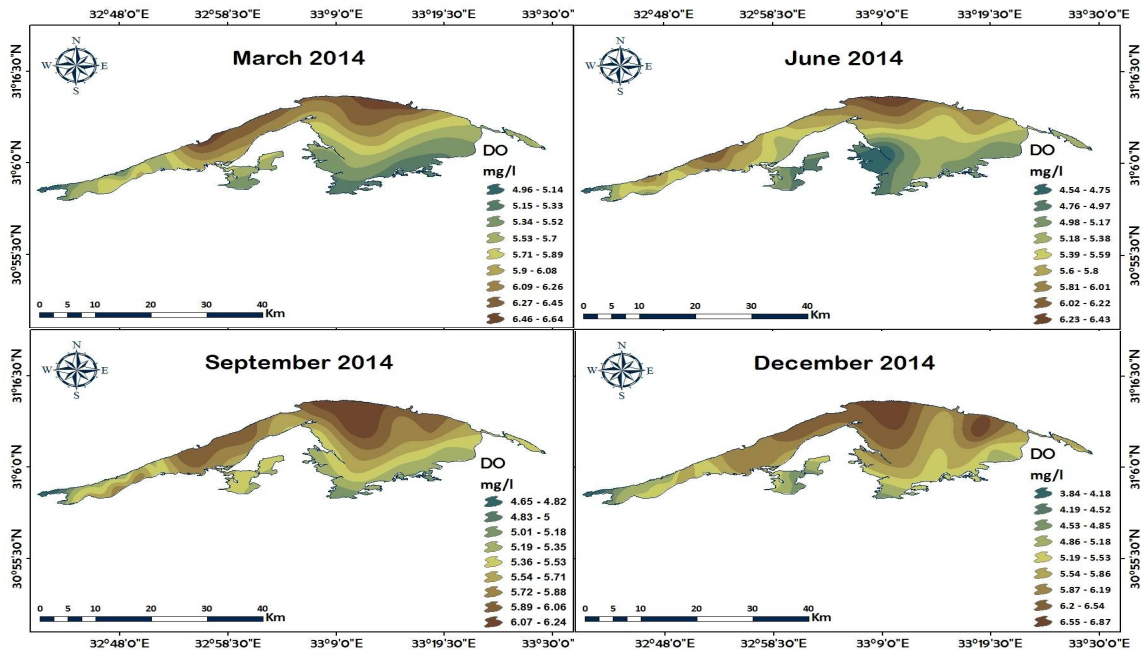


Fig. (7): Cartographic maps of DO distribution as obtained from GIS analysis in Bardawil Lagoon during March, June, September and December 2014.

V. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to use *in situ* water measurements combined with Landsat-8 Operational Land Imager (OLI) data and ancillary data in a geographic information system (GIS) as a tool in deriving water quality indicators of Bardawil Lagoon for sustainable management. Correlation and stepwise regression models were developed between each of the WQP measurements and the reflectance of image data. The current study indicated that despite the variation in statistical response, there existed a perfect correlation between selected WQPs (salinity, pH and dissolved oxygen) and Landsat-8 OLI data in Bardawil Lagoon. The efficiency of the proposed algorithms was investigated based on the values of bias and root-mean-square error. As there was a little variation between Landsat-8 predicted values and measured concentrations, this study proved that Landsat-8 data were useful in quantifying water quality dynamics and preparing digital cartographic maps. The models and methods used in this study for retrieval of water quality indicators from Landsat-8 are promising and can be frequently applied to Bardawil Lagoon for sustainable water quality monitoring.

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International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 8, August 2016

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