A GIS-based spatiotemporal study of the variability of water quality in the Dubai Creek, UAE

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ABSTRACT

This paper presents the outcomes of a study on the water quality of Dubai Creek which aimed to assess its eutrophication status. Field water quality data from stations along the creek collected in 2012 and 2013 were used. Ordinary least squares (OLS) and spatial autocorrelation analyses were used as part of geographic information system (GIS)-based exploratory regression analysis to study the relationship between chlorophyll-a and nutrients, specifically total nitrogen and phosphate. Multiple logistic regression analysis was used to study the vulnerability of the creek to eutrophication. Results showed unique trends of spatiotemporal variability of chlorophyll-a and nutrients. OLS modeling showed high correlation between field and modeled chlorophyll-a values between Al Garhoud Bridge and Sanctuary stations, located about 2 km upstream and downstream of the Sewage Treatment Plant (STP) Outfall station. Furthermore, results showed the lower half of the creek was more vulnerable to eutrophication than the upper, which was believed to be due to the location of the STP station, poor flushing, shallow water depth, and irregular circulation patterns in the creek. Accordingly, this study recommends development of a mitigation plan in order to control the levels of nutrients in the creek.

Key words | Dubai Creek, exploratory regression, multiple logistic regression, spatial autocorrelation, water quality

INTRODUCTION

In surface water bodies, high concentrations of nutrients, mainly phosphorus and nitrogen compounds are known to cause eutrophication, a process of accelerated growth of algae and other forms of plant. Given that chlorophyll-a is a main indicator of algal growth, investigation of the relationship between chlorophyll-a and nutrients has been the subject of many research studies (Gašparovič et al. 2011; Yang et al. 2013). A common objective among these studies was the development of a model for predicting chlorophyll-a concentration if the levels of nutrients in the water body are known. Hakanson & Eklund (2010) developed a non-linear model that relates chlorophyll-a to total phosphorus based on water quality data from 500 locations. Guildford & Hecky (2000) developed a model that relates chlorophyll-a to total phosphorus and nitrogen.

An indication of eutrophication in addition to the evident excessive algal growth is the decrease of dissolved oxygen content in the water, a condition known as hypoxia (Johansson 1997). Also, eutrophication is known to increase water turbidity. Eutrophication is commonly linked to human activities that discharge effluents with high concentrations of nutrients in the water. Many studies have presented the risks of eutrophication (Arhonditsis et al. 2007; Kitsiou & Karydis 2011; Fernández et al. 2014) and its environmental impacts and financial losses (Borja & Dauer 2008, Gudimov et al. 2010).

Dubai has rapidly developed in the past decade and is now a major center of attraction in the Middle East. However, these developments have resulted in significant impacts on the environment (Al-Azab et al. 2005). The Dubai Creek, a 14-km long saltwater body, is situated at the heart of the urban development in Dubai and divides the city into two areas. The creek is mainly used for transportation, trade, and recreation. Urbanization and the
great growth in population have taken its toll on the creek; this has been exacerbated by it being a poorly flushed water body (Abu-Hilal et al. 1994; Hassan et al. 1995). One major reason for the creek’s water quality degradation is the treated sewage discharge from Al-Aweer Sewage Treatment Plant (STP) (Ismail 1992; Saunders et al. 2007). Moreover, the number of ships and boats using the creek has increased rapidly in recent years as Dubai has expanded as a center of trade and tourism. Likewise, the landscape areas on the banks of the creek may have adverse effects on the water quality when fertilizers get washed out by runoffs. Additionally, the stagnant water condition at the bottom of the creek due to poor flushing of the entire water body is considered to be a major factor in pollution of the creek (El-Sammak 2001; Howari & El-Saiy 2008).

Dubai Municipality is operating several stations on the Dubai Creek and along the Dubai coast for water quality monitoring. Major water quality parameters measured at these stations include chlorophyll-α, nitrate, phosphate, dissolved oxygen, turbidity, salinity, and pH. In the past few years, data recorded at these stations showed increased levels of chlorophyll-α and nutrients in the creek to amounts above levels set by the Organisation for Economic Co-operation and Development for assessing the ‘eutrophic condition’ of water bodies (OECD 1982). This situation has called for systematic investigation following the harmful algal bloom events (red-tides) in the Dubai and Arabian Gulf area in 2008 and 2009 which caused massive fish kills and forced closure of beaches (Zhao & Ghedira 2014). The Emirates Wildlife Society has attributed the events to nutrient pollution and high temperatures (Landais 2008). Figure 1 shows the locations of the monitoring stations along the creek (Ali et al. 2013). The water quality data obtained from Dubai Municipality for this study were delivered as quarterly averages for 2012 and 2013. Table 1 shows Quarter 2 of 2012 data as a sample of the water quality data used in this study.

The objectives of this paper were to: (1) analyze the spatiotemporal variability of water quality parameters in the Dubai Creek, specifically chlorophyll-α, total nitrogen, and phosphate; (2) study the relationship of chlorophyll-α to total nitrogen and phosphate; and (3) investigate the vulnerability of the creek to eutrophication. Geographic information system (GIS)-based spatiotemporal analysis was used to understand the spatiotemporal variability of major water quality parameters and to discover the underlying patterns and correlations. Exploratory regression (ER) was used to study the relationship between chlorophyll-α and nutrients, and multiple logistic regression (MLR) was used to explore the vulnerability of the creek to eutrophication.
METHODS

Examining variability of chlorophyll-a and nutrients and ER analysis of their relationship

ER modeling and spatial autocorrelation analysis were carried out in ArcGIS 10.1 in order to examine the spatiotemporal trends and seasonal patterns of chlorophyll-a and nutrients in the Dubai creek using the field data collected in 2012 and 2013. For creating the density grids (i.e., the grid-based representations) of the spatial distribution of the three parameters in the creek, the inverse distance weighted interpolation method was used with a cell size of 10-m.

ER analysis was carried out in ArcGIS 10.1 to model the relationship between chlorophyll-a, total nitrogen, and phosphate. As part of ER analysis, ordinary least squares (OLS) analysis was used, followed by spatial autocorrelation analysis. OLS regression is a technique for linear modeling of a dependent variable that relates to independent or explanatory variables. OLS analysis is known to work efficiently with field data (Tian & Wiens 2006). The general form of the OLS regression model used in this study is shown below:

$$z = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \quad (1)$$

where $z$ is the dependent variable, $x_1, x_2, x_n$ are $n$ independent variables, $a_0$ is the intercept of the linear model, and $a_1, a_2, \ldots, a_n$ are the model coefficients.

Spatial autocorrelation analysis in ArcGIS 10.1 is based on Moran’s index, and it measures the correlation based on the features’ locations and attributes and was therefore used to identify clusters of total nitrogen and phosphate in the creek as they correlate to those of chlorophyll-a.

Use of MLR analysis to study the vulnerability of the creek to eutrophication

In this study, a MLR model was used to determine the probability of occurrence of eutrophication considering total nitrogen and phosphate as the independent variables and chlorophyll-a as the dependent. MLR is a multivariate statistical method that considers independent variables that influence the occurrence of a dependent variable (Shirzadi et al. 2012). In order to use MLR efficiently, the use of independent variables that are uncorrelated or have maximum variances is normally recommended. The MLR analysis determines the probability of occurrence of a dependent variable if its independent variables are known. In this study, the estimated values of the probability of occurrence of eutrophication were used to define levels of vulnerability of the creek to eutrophication. The MLR model used in this study has a function of $f(z)$ such that $z$ is the dependent variable that $1 \geq f(z) \geq 0$, and has the following form:

$$f(z) = \frac{1}{e^{-\frac{z}{c_1+c_2+c_3}}} \quad (2)$$

Table 1 | Sample of selected water quality parameters used in this study (Quarter 2 of 2012)

<table>
<thead>
<tr>
<th>Station name</th>
<th>Salinity (ppt)</th>
<th>pH</th>
<th>Chlorophyll (μg/L)</th>
<th>Total nitrogen (mg/L)</th>
<th>Phosphate as P (mg/L)</th>
<th>Dissolved oxygen (mg/L)</th>
<th>Nitrites (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creek mouth</td>
<td>39.72</td>
<td>7.86</td>
<td>4.6</td>
<td>0.52</td>
<td>0.01</td>
<td>5.08</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Hyatt Regency</td>
<td>39.08</td>
<td>8.04</td>
<td>15.3</td>
<td>0.69</td>
<td>0.02</td>
<td>6.66</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Abra</td>
<td>38.43</td>
<td>7.97</td>
<td>5.9</td>
<td>1.61</td>
<td>0.1</td>
<td>3.65</td>
<td>0.26</td>
</tr>
<tr>
<td>Wharfage</td>
<td>38.41</td>
<td>7.96</td>
<td>6.4</td>
<td>1.74</td>
<td>0.1</td>
<td>3.71</td>
<td>0.31</td>
</tr>
<tr>
<td>Floating Bridge</td>
<td>34.84</td>
<td>8.46</td>
<td>57.5</td>
<td>2.9</td>
<td>0.26</td>
<td>10.91</td>
<td>1.76</td>
</tr>
<tr>
<td>Al Garhoud Bridge</td>
<td>36.55</td>
<td>8.3</td>
<td>57.8</td>
<td>3.72</td>
<td>0.39</td>
<td>10.27</td>
<td>2.34</td>
</tr>
<tr>
<td>Dubai Festival City</td>
<td>34.7</td>
<td>8.6</td>
<td>69.5</td>
<td>2.43</td>
<td>0.21</td>
<td>15.06</td>
<td>1.52</td>
</tr>
<tr>
<td>STP Outfall</td>
<td>35.33</td>
<td>8.56</td>
<td>69.3</td>
<td>2.03</td>
<td>0.18</td>
<td>10.25</td>
<td>1.13</td>
</tr>
<tr>
<td>Al Jaddaf</td>
<td>35.29</td>
<td>8.56</td>
<td>74.8</td>
<td>2.08</td>
<td>0.18</td>
<td>13.93</td>
<td>1.05</td>
</tr>
<tr>
<td>Sanctuary</td>
<td>36.02</td>
<td>8.74</td>
<td>92.6</td>
<td>1.05</td>
<td>0.08</td>
<td>15.41</td>
<td>0.42</td>
</tr>
</tbody>
</table>
where $c_0$ is the intercept, $x_1$ and $x_2$ are the independent variables and $c_1$ and $c_2$ are model coefficients.

RESULTS AND DISCUSSION

Examining variability of chlorophyll-\(a\) and nutrients

Spatial variation

According to the results obtained in ArcGIS 10.1 for chlorophyll-\(a\) concentrations over the creek (Figure 2), the first quarter of 2012 showed low levels throughout except around the Wharfage and the Floating Bridge stations with values of 40.8 \(\mu\)g/L and 51.2 \(\mu\)g/L, respectively. The second quarter showed an increase in the concentrations from the Floating Bridge station to the bottom of the creek in range from 57.5 to 92.58 \(\mu\)g/L. These numbers indicated an algal bloom event in this region. As expected, the concentrations dropped in the next quarter to a minimum of 41.58 \(\mu\)g/L. This decrease continued until the last quarter of 2012 and the first quarter of 2013. However, the second quarter of 2013 showed a notable rise in chlorophyll-\(a\) levels, ranging from 128.4 \(\mu\)g/L to 192.64 \(\mu\)g/L. This was an indication of a second algal bloom event that occurred within the period of 2 years. The third quarter witnessed a drop from 192.64 \(\mu\)g/L to 6 \(\mu\)g/L at the creek’s mouth.

Total nitrogen in water is essential for aquatic plant and animal life, and an excess of it is an indicator of pollution, especially high concentrations of chlorophyll-\(a\). Optimum total nitrogen values are between 0.5 mg N/L and 1.0 mg N/L (Figure 3). Analysis of the 2012 water quality data showed that total nitrogen levels were high in the first and last quarters around the middle and lagoon parts of the creek. These areas had values as high as 15 mg N/L, indicating pollution. In 2013, the high levels of total nitrogen indicate the migration of pollution towards the lagoon part of the creek. The relationship between the total nitrogen and chlorophyll-\(a\) is not very clear from Figures 2 and 3.

The optimum range for phosphate is 0.05 mg P/L to 0.1 mg P/L for a waterbody. Algae consume it as nutrient, hence it is one of the major reasons for eutrophication. The results showed that phosphate levels were within the optimum range at the mouth of the creek (Figure 4). However, higher levels of phosphate (more than 0.1 mg P/L) were observed at the center and at the bottom of the creek in the first quarter of 2012 (0.5 mg P/L), the fourth quarter of 2012 (0.67 mg P/L), and first quarter of 2013 (0.8 mg P/L). This was similar to the times when chlorophyll-\(a\) levels were low. It is indicative of increased phosphorus levels due to the release from dead algae.

Temporal variation

To understand the temporal variation of the major nutrients with chlorophyll-\(a\), multivariate plots have been created for all 10 monitoring stations in order to illustrate the variation patterns of the concentrations of nitrate, total nitrogen, and phosphate with chlorophyll-\(a\). Since most of the concerns of water quality were around the middle and bottom half of the creek, the analysis focused on selected sampling stations around those locations. At Floating Bridge station, it appears that nitrate was the main nutrient that triggered the increase in algal growth (Figure 5). The rise in the amount of nitrate led to an accelerated algal growth in the second quarter of 2013 once again. It could be due to the nitrogen in surface runoff from the nearby green areas.

The results from Al-Garhoud station illustrated an evident algal increase with increase in nitrate and phosphate concentrations (Figure 6). The two peaks in chlorophyll-\(a\) concentration coincided with the two peaks in nitrate and phosphate concentrations. It is noteworthy that the nutrient concentrations at this station and the remaining four stations between this location and the lagoon part of the creek were higher than the concentrations at the other stations. Possible reasons for this pattern could be the presence of effluent from the Al Aweer Sewage Plant in the lagoon part of the creek in addition to the expected nutrient-rich surface runoffs from the landscapes on the two sides of the creek. Moreover, the number of leisure and transport ships that dock in this area was significantly higher than that in other locations.

At the Festival City station, a pattern was observed at the beginning of 2012 when nitrate and total nitrogen concentration were high and led to an increased algal growth in the second quarter of 2012 (Figure 7). However, the increase in nutrients in the fourth quarter of 2012 and the first quarter of 2013 resulted in a slight increase in the chlorophyll
Figure 2 | Maps of chlorophyll-a concentrations in 2012 and 2013.
Figure 3 | Maps of total nitrogen concentrations in 2012 and 2013.
Figure 4 | Maps of phosphate concentrations in 2012 and 2013.
Figure 5 | Floating Bridge (scale: nitrate × 10; phosphate × 10).

Figure 6 | Al-Garhoud Bridge station (scale: nitrate × 10; phosphate × 10).

Figure 7 | Dubai Festival City station (scale: nitrate × 10; phosphate × 10).
levels in the second quarter of 2013. This is indicative of a lag in chlorophyll-a formation compared to that of nutrients, which is consistent with the norm that chlorophyll-a formation takes time to respond to the elevated nutrient concentrations.

The same water quality pattern to that at the Festival City station was observed at Jadaf station. It was a repetitive cycle of increase in the amount of nutrients which consequently resulted in an increase of chlorophyll-a (Figure 8). However, no considerable lag time was observed at this location. The cycle occurred twice over the 2-year period. It is interesting that the concentrations recorded at this station were higher than previous stations and the pollution pattern occurred twice over the 2-year period, indicating that this area was prone to excessive pollution.

The results of the STP Outfall station showed a significant increase in the amount of nutrient around the middle of 2012 (Figure 9). This was probably a consequence of the ongoing pollution in this area. In 2013, nutrient variations were similar to that of chlorophyll-a concentrations. This pattern was consistent with that of some of the previously discussed stations.

The results from the Sanctuary station, located in the lagoon part of the creek, indicated a lag in chlorophyll-a concentrations compared to the nutrient concentrations (Figure 10). A decrease in nutrients caused a drop in algal growth, as expected. However, due to pollution, a massive increase in the amount of nutrients was observed, resulting in a late algal increase in the middle of 2013. As expected, a decrease in nutrients occurred due to the high consumption of nutrients by algae. This lag in appearance of the
OLS regression modeling

Quarterly-based OLS models of the relationship between chlorophyll-α (dependent variable) and total nitrogen and phosphate (independent variables) were created. Like any time-series data, the quarterly water quality data used in this study have seasonal and trend-cycle components, the first of which was examined in the preceding section. In this section, the trend-cycle component is examined through OLS modeling. Weighted means of the quarterly OLS model coefficients have been used to develop annual OLS models for 2012 and 2013, respectively, using the inverse variances of quarterly-based OLS models as weights. Table 2 shows the annual OLS model variables, coefficients, and results developed for 2012 and 2013. As Table 2 shows, the coefficients of the OLS model of total nitrogen in 2012 and 2013 were both positive, indicating a positive correlation with chlorophyll-α. The coefficients of phosphate were negative in 2012 and positive in 2013, indicating that other factors affect the relationship, for example, some of the lag times observed in the previous analysis. The $R^2$ values of the two linear models were 0.62 and 0.75, respectively; these values are consistent with those obtained by Brown et al. (2000) and Hoyer et al. (2002). As shown in Table 2, the variance inflation factor (VIF) values of the OLS models were less than 7.5, indicating a lack of redundancy in using these variables. The Koenker statistics values were 2.662 and 3.004, indicating consistent relationships.

Spatial autocorrelation analysis

Spatial autocorrelation analysis was used to study the spatial dependence in each of total nitrogen, phosphate and chlorophyll-α by computing Moran’s I indices. Table 3 summarizes Moran’s I indices obtained for the three parameters. The Moran’s I values indicate a degree of spatial dependence in each of the parameters, but not of high statistical significance. Since the levels of spatial autocorrelation of the three parameters are not high, the correlation coefficients obtained in OLS regression modeling (Table 2) should be representative of the real association between the three parameters. This is because significant spatial autocorrelation normally exaggerates correlation and regression precision.
Table 3 | Summary of spatial autocorrelation analysis (Moran’s I indices) in 2012 and 2013

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nitrogen</td>
<td>0.2514</td>
<td>0.2372</td>
</tr>
<tr>
<td>Phosphate</td>
<td>0.2325</td>
<td>0.2105</td>
</tr>
<tr>
<td>Chlorophyll-a</td>
<td>0.2028</td>
<td>0.1556</td>
</tr>
</tbody>
</table>

In order to develop annual spatial correlation maps between the three parameters, weighted means of quarterly-based correlation coefficients were estimated and used, utilizing the inverse variances of quarterly-based models as weights. Spatial correlation maps were created for 2012 and 2013 data as shown in Figure 11. These maps show the correlation between OLS models and field chlorophyll-a values in the creek in terms of the correlation coefficient. As shown in the 2012 map, there was higher correlation between the OLS model and field values of chlorophyll-a in the lagoon and middle parts of the creek than that at the mouth of the creek. The 2013 map shows high correlation between the locations of Al Garhoud and the STP Outfall station. Furthermore, the two maps of 2012 and 2013 in Figure 11 show a similar level of correlations between the OLS model and field values of chlorophyll-a along the segment of the creek located between Al Garhoud and Sanctuary stations. Given that the STP Outfall station is located approximately halfway along this segment of the creek, the high correlation between the OLS model and field chlorophyll-a values reflects some robustness of the OLS models.

Examining the vulnerability of the creek to eutrophication

The MLR model of Equation (2) was used with total nitrogen and phosphate as the independent variables and accordingly maps of the probability of occurrence of eutrophication in the creek in 2012 and 2013 were produced (Figure 12). Results showed that the probability of occurrence of eutrophication in the bottom half of the creek was higher than that at the upper half in 2012 and 2013. The lagoon part of the creek, which is located to the south of the location of the STP Outfall station, had the highest probability of occurrence of eutrophication in 2012. However, the lagoon part of the creek had medium probability of occurrence of eutrophication in 2013. The part of the creek to the north of the STP Outfall station had the highest probability.
probability in 2013. This was explained by the nutrient-rich effluent at this location of the STP Outfall station, poor flushing of the bottom part of the creek, and the irregular circulation pattern in the creek. Three levels of vulnerability of the creek to eutrophication (Figure 13) were created from the probability of occurrence of eutrophication using the natural breaks method in ArcGIS 10.1. The results showed that in 2012 and 2013, the lower half of the creek was consistently more susceptible to eutrophication than the upper half.

Figure 12 | Maps of the probability of occurrence of eutrophication in 2012 and 2013.

Figure 13 | Vulnerability of the creek to eutrophication in 2012 and 2013.
CONCLUSIONS

The pollution pattern observed in the creek was a byproduct of the rapid development in the area due to the increased level of anthropogenic activities. Total nitrogen and phosphate have increased due to pollution, accelerating algal growth in the creek. Spatially, it is evident that pollution occurs at the center of the creek and makes its way towards the mouth and lagoon part of the creek. Possible reasons for this pattern were the location of the nutrient-rich effluent from Al Aweer Sewage Plant at the STP Outfall station, the poor flushing of the lagoon part of the creek, surface runoff from landscapes on the banks of the creek, and irregular circulation patterns in the creek. OLS modeling was used to study the relationship between chlorophyll-α and nutrient, specifically total nitrogen and phosphate for 2012 and 2013. OLS modeling provided insight on the relationship between chlorophyll-α and nutrients in the creek with estimated $R^2$-values of 0.62 and 0.75 in 2012 and 2013, respectively. Relatively good fit between the OLS models and field data was observed in the lower half of the creek. The highest correlation was observed along the part of the creek located between Al Garhoud Bridge and Sanctuary stations. Given that the STP Outfall station is located approximately halfway through this segment, the high correlation between predicted and field chlorophyll-α values along this part of the creek is an indication of the robustness of the OLS models.

Results showed that the probability of occurrence of eutrophication in the bottom half of the creek was higher than that in the top half. Based on this study, a mitigation plan is needed in order to reduce the levels of nutrients in the creek. This includes control of total nitrogen and phosphate concentration in the discharge from Al Aweer Sewage Plant as well as the control of the non-point source pollution, specifically nutrient-rich surface runoff from landscapes bordering the creek.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Dubai Municipality by providing water quality data and the support of the Office of Research at the American University of Sharjah through faculty research grants FRG12-2-24 and FRG14-2-16.

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First received 9 April 2015; accepted in revised form 22 August 2015. Available online 29 September 2015