EnvironmentAsia
The international journal by the Thai Society of Higher Education Institutes on Environment

EnvironmentAsia 14(3) 2021 23-36
DOI 10.14456/ea.2021.20
ISSN 1906-1714; ONLINE ISSN: 2586-8861

Seasonal and Spatial Variation of Water Quality in Cardiff Bay: Analysis of Historic Data and Future Trend

Md. Sultanul Islam[1*], Md. Nazmul Islam[2], and Syeda Marzia[3]

[1]*Department of Civil Engineering, Presidency University, Dhaka, Bangladesh*
[2]*Department of Chemistry, University of Rajshahi, Rajshahi, Bangladesh*
[3]*Department of Civil Engineering, Daffodil International University, Dhaka, Bangladesh*

*Corresponding author: sultanuli@pu.edu.bd
Received: February 2, 2021; Revised: February 27, 2021; Accepted: April 1, 2021

Abstract

The construction of a barrage in Cardiff, United Kingdom at the confluence of the rivers, the Taff and Ely, created a 200 hectares freshwater lake in 2001. The study investigates the water quality trend in Cardiff Bay from January 2001 to September 2005, covering both summer and winter seasons. Eight water quality parameters were analyzed to assess any significant pattern of seasonal variation and spatial distribution. The overall mean value of pH was 8.03; BOD, Ca, Mg, Cl, hardness, TSS were 1.20, 6.05, 3.33, 3.45, 11.72, 2.74 mg/L respectively; and orthophosphate (OP) was 0.08 μg/L. Mean values were mostly found higher in summer as compared to winter, notably in 2001. In summer, higher values of pH, BOD and hardness were attributed to enhanced photosynthesis leading to production of less carbonic acid, bacterial growth and dissolution of Ca and Mg respectively. The decreasing pattern of Cl and OP was reflected in higher BOD and little possibility of eutrophication. The pattern of TSS was non-uniform and random. The water in Cardiff Bay, compared with relevant data of three artificial lakes, was found to be safe and within the guidelines. A future trend analysis suggested that pH, Mg, Cl and OP would decrease; BOD and TSS would increase marginally; Ca and hardness would remain unchanged in the site.

Keywords: Seasonal variation; Spatial distribution; Physico-chemical; Water quality; Freshwater lake; Cardiff Bay

1. Introduction

Lakes are considered one of the most important freshwater resources on the earth. Freshwater lakes, both natural (e.g., Lake Baikal, Russia; Lake Tahoe, USA) and artificial (e.g., Lake Volta, Ghana; Cardiff Bay, UK), are significant for restoring natural ecosystems, environmental protection and socio-economic benefits (Sharifinia *et al.,* 2013; Adrian *et al.,* 2016). Artificial water bodies are built by direct physical alteration, movement or realignment of a natural water body (Islam and Chowdhury, 2020) or purposefully, e.g., by capturing surface runoff or atmospheric precipitations. Artificial lakes are created for multipurpose usage, e.g., potable water supply (Islam, 2006; US Geological Survey, 2020), hydroelectric power generation (Leentvaar, 1993; Ghansah *et al.,* 2016), flood control (Watters, 1999), tourism and recreational activities (Lee, 2019). Cardiff Bay is such a purpose-built water body created at the confluence of river Taff and river Ely. This bay area had undergone major redevelopments including construction of the Cardiff Bay Barrage and the waterfront infrastructures (Islam and Chowdhury, 2020). The 1.1 km long barrage was designed to impound freshwater from the rivers Taff and Ely to create a 200 hectares freshwater lake, with a constant water level (Falconer and Lin, 2004). The distinctive freshwater lake was introduced as the centerpiece of an urban regeneration scheme that included housing, commerce, leisure, sports facilities and industrial development.

Impoundment fundamentally alters the dynamics of estuaries in terms of its sedimentation rates, pattern and water quality (Wright and Worrall, 2001). Water quality represents physical, chemical and microbiological conditions of the water and its suitability for specific usage (El-Serehy *et al.,* 2018; NOAA, 2020). In recent years, deterioration of surface water quality due to increased pollution has emerged as a serious global concern. Monitoring and assessing water quality are therefore significant for ensuring ecological balances, socio-economic benefits, as well as sustainable protection and proper management (El-Serehy *et al.,* 2018; Lee, 2019) of freshwater lakes.

Little had been known in context of water quality trends and the effects of water chemistry parameters on aquatic lives since the bay was converted into a freshwater environment. Water quality is a critical factor for shallow freshwater lake like Cardiff Bay, because even slight deteriorations might cause significant adverse effect on water users and aquatic wildlife. Cardiff Bay has already been designated as a sensitive area (Eutrophic) under the Urban Waste Water Treatment Directive, due to very high concentration of total phosphorus and chlorophyll-a (Merrix-Jones *et al.,* 2013). Extensive water quality monitoring data were collected between 2001 and 2005. Based on those collected data, in this study, the authors investigate spatial and seasonal variations of water quality in Cardiff Bay. Water quality indicators e.g., pH, BOD, Ca, Mg, Cl, hardness, TSS and OP have been analyzed here with the aim to provide site-specific information on water quality effects on the biodiversity of aquatic lives, and to assist in the design of pollution management strategies. Moreover, the study forecasts the water quality trends for next few decades by extrapolating the best-fitted regression curves or trend lines.

2. Materials and Methods

2.1 Study Area

The study area, Cardiff Bay, is located in the south of Cardiff, capital of Wales, United Kingdom at latitude 51°27′28″N and longitude 3°08′24″W. This relatively shallow freshwater lake has a surface area of 200 hectares with a mean depth of approximately 4.5 m and a maximum depth of around 13 m (Lee, 2019). A total of 11 monitoring sites were considered in the study which is shown in Figure 1.

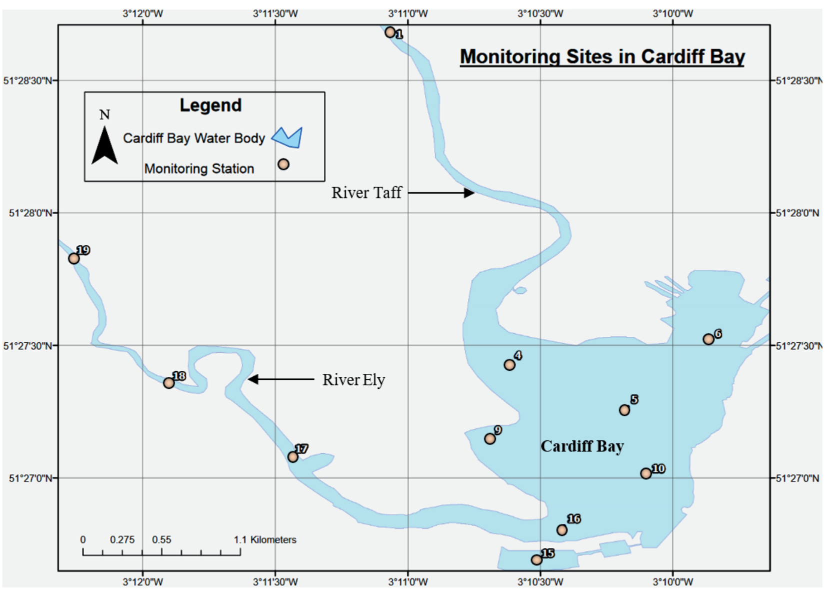

Figure 1. The study area showing the positions of the 11 monitoring sites

2.2 Data Collection

Cardiff Harbor Authority (CHA) is the main body responsible for continuous monitoring and management of water quality in the bay. Water samples were collected from set locations within the bay and feeding rivers in accordance with a monitoring program agreed by the Natural Resources Wales. Several water quality parameters were continuously monitored using YSI buoys and the collected data was telemetered every 15 minutes via radio link to a computer located in CHA office. Six monitoring stations were employed with high precision, calibrated instruments within the bay, river Taff and river Ely to measure dissolved oxygen (DO), temperature, pH, conductivity and turbidity at one meter below the surface level in all locations, and at one meter above the bed of the bay at three locations (Lee, 2019). To update the system and enable users with access to live water quality data, the buoys are connected to YSI's EcoNet system, which is publishing live data to a dedicated website since 2008 (Hanson, 2011). The data analyzed for this study were collected from CHA through Catchment Research Group, Cardiff University, from January 2001 to September 2005.

2.3 Data Analysis

The original datasets obtained were categorized into two groups: seasonal and site-specific. Two distinctive seasons, summer and winter, were considered for data analyses. Summer and winter data sets represented May to September and October to April in this study, respectively. Site-specific or spatial data were in accordance with sampling sites as shown in Figure 1. Eight physico-chemical water quality parameters were considered in this study, based on their potential impacts on lake ecosystem. These included pH, biochemical oxygen demand (BOD), calcium (Ca), magnesium (Mg), chloride (Cl), total hardness, total suspended solids (TSS) and soluble reactive phosphate or orthophosphate (OP). All the parameters were expressed in mg/L unit, except for pH and OP (μg/L).

2.4 Statistical Analyses

The collected data were subject to both descriptive and multivariate statistical analysis. The datasets, either seasonal or site-specific, were treated separately for analyzing basic statistical parameters and for making cross-tabulations and cross-plots. The SPSS (version 22.0) and STATGRAPHICS Centurion (version 18.1.12) statistical software package, and Microsoft Excel (version 12.0.4518.1014) were employed for the purpose. ANOVA and Levene's Variance test were applied for analyses of variance of the data (Table 1).

2.5 Spatial and Seasonal Variation

Spatial variation in water quality is one of the main features of different types of water bodies and is largely determined by the hydrodynamic characteristics. Water quality cannot usually be measured in only one location within a water body but may require a grid or network of sampling sites. Chapman (1996) suggested that temporal variability can occur to one of the following reasons:

- Diel variability (24-hour variations) limited to biological cycles
- Days-to-months variability mostly in connection with climatic factors and to pollution sources
- Seasonal hydrological and biological cycles
- Year-to-year trends, mostly due to human and hydrological influences

Variation of different water chemistry parameters due to seasonal changes is a common feature for freshwater environment. Variables like pH and total suspended solids may vary significantly in the respective receiving water bodies (Islam and Chowdhury, 2020).

2.6 Future Trend Analysis

To assist future water quality management of the bay, an attempt was made to extrapolate the best-fit regression curve or trend line up to 50 years (Figure 5) using CurveExpert Professional (version 2.6.5) software. The trend of one parameter, pH, was cross-checked with actual data received from CHA website, which proved to be accurate enough to validate our analysis.

3. Results and Discussion

3.1 Descriptive Statistics of the Parameters

The descriptive statistics of the data (n = 824) for eight physico-chemical parameters for the two seasons (summer and winter) are summarized in Table 1.

In relation to statistical analyses, the variance of each parameter was sub-divided into two components in ANOVA table: a between-group component and a within-group component. Since the P-value of the F-test was less than 0.05, there was a statistically significant difference between the means of the eight variables. Levene's test showed a statistically significant difference among the standard deviations at the 95% confidence level as the P-value was less than 0.05. Kruskal-Wallis and Mood's Median tests (Islam *et al.,* 2018) also confirmed that the medians of the samples were significantly different at the 95% confidence level.

3.2 Seasonal and Site-specific Distribution Pattern

It was generally observed that mean concentration levels of the parameters were comparatively higher in summer than in winter (Table 1), especially in 2001 when the bay was transformed into a freshwater lake. The seasonal and site-specific variations are described below:

3.2.1 pH

The pH of water acts as a function of solubility and hence bioavailability of nutrients and minerals for aquatic lives (Islam and Chowdhury, 2020). The pH ranging from 6 to 9 is suitable for the existence of most biological life (Metcalf and Eddy, 2003) and approved by regulators such as European Union (2019) and DEFRA (2014). Overall, a slight increasing trend in the magnitude of pH was observed during summer seasons; however, the variation was not of much significance. Although the mean pH was 8.03, the highest value 8.21 was observed in summer 2003 and 2005 (Figure 2). The slight increase in pH was attributed to increased photosynthesis in summer that reduces CO_2 and thereby producing less carbonic acid ($CO_2 + H_2O = H_2CO_3$) (Islam and Chowdhury, 2020) and the process was favored by the growth of excessive algae or phytoplankton at the beginning of year 2001. In terms of spatial distribution, higher mean values were found at site 15 compared to other sites in both seasons. The analysis revealed that the effect of pH on water quality at the bay is marginal.

Table 1. Statistical analyses of the studied parameters in Cardiff Bay

Parameter	Season	Concentration (mg/L)[a]						
		Range (Min-Max)	Mean ± SE	95% CI for mean	Median	Standard Deviation	Variance	Skewness
pH	Summer	7.79 - 8.21	8.116±0.045	7.991-8.241	8.110	0.100	0.010	-0.617
	Winter	7.85 - 7.99	7.950±0.026	7.879-8.021	7.970	0.057	0.003	-2.024
TSS	Summer	2.40 - 3.40	2.682±0.183	2.175-3.189	2.570	0.408	0.167	2.044
	Winter	2.00 - 3.33	2.672±0.247	1.986-3.358	2.450	0.552	0.305	0.162
BOD	Summer	1.12 - 1.41	1.234±0.054	1.083-1.385	1.240	0.122	0.015	0.600
	Winter	1.05 - 1.29	1.170±0.046	1.043-1.297	1.170	0.102	0.010	0.000
Ca	Summer	5.77 - 6.76	6.174±0.162	5.725-6.624	6.130	0.362	0.131	1.171
	Winter	5.64 - 6.04	5.870±0.073	5.668-6.073	5.920	0.163	0.027	-0.653
Mg	Summer	3.26 - 3.61	3.454±0.067	3.269-3.640	3.410	0.149	0.022	-0.092
	Winter	2.99 - 3.29	3.184±0.052	3.041-3.327	3.220	0.115	0.013	-1.594
Hardness	Summer	11.65 - 12.81	12.078±0.210	11.519-12.637	11.960	0.450	0.203	1.338
	Winter	10.92 - 11.51	11.254±0.102	10.972-11.536	11.310	0.227	0.052	-0.688
Cl	Summer	3.39 - 3.95	3.546±0.104	3.257-3.835	3.340	0.233	0.054	1.933
	Winter	3.13 - 3.42	3.278±0.046	3.150-3.406	3.270	0.103	0.011	-0.139
OP	Summer	0.05 - 0.16	0.098±0.018	0.047-0.149	0.090	0.041	0.002	0.752
	Winter	0.05 - 0.07	0.062±0.004	0.052-0.072	0.060	0.008	0.000	-0.512

[a] pH is unitless and OP is expressed in µg/L

3.2.2 BOD

The BOD_5 is a measure of the amount of oxygen that bacteria will consume in five days at 20°C while decomposing organic matter under aerobic conditions (Masters and Ela, 2008). Unpolluted waters typically have BOD values of 2.0 mg/L or less (Chapman, 1996; EU, 2019). In the present study, BOD values were varied from 1.12 to 1.41 mg/L in summer and 1.05 to 1.29 mg/L in winter respectively. A slight increasing trend in BOD was observed with respect to time. Seasonal fluctuations were prominent in terms of summer and winter values for several sites, especially for sites 6, 9, 16 and 18. An increase in BOD level reflects in depletion of oxygen level, which is life-threatening to countless fishes and bottom-dwelling organisms in lakes. To overcome this problem, an extensive aeration system was embedded in the lakebed so that oxygen level was always kept above a statutory 5 mg/L (Merrix-Jones *et al.,* 2013). In addition, regular skimming was carried out to remove debris and algal scum from the lake surface (Islam and Chowdhury, 2020).

3.2.3 Ca and Mg

Among the major cations present in lake waters, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} are of particularly significant (Amoo and Komolafe, 2018; Olalekan *et al.,* 2015). Calcium is an important nutrient for aquatic organisms, while magnesium is essential for chlorophyll growth and acts as a limiting factor for growth of phytoplankton (Qureshimatva *et al.,* 2015). Magnesium usually occurs in lower concentration than calcium, since the dissolution of magnesium rich minerals is a slow process (Arulneyam and Premsudha, 2018).

The overall mean concentrations of Ca and Mg were found 6.022 and 3.319 mg/L respectively. Seasonal fluctuations for Ca and Mg were not significant as the concentration levels followed similar patterns except for Summer 2005, where Ca showed a higher value of 6.76 mg/L (Figure 2). An increasing trend of Ca was observed for the sites 15-19, whereas significantly increased Mg was found at site 15 (closer to the barrage) for both seasons (Figure 3). Again, Mg showed comparatively lower values than the mean in summer for the sites 17-19, situated in the river Ely and far from the barrage. The difference between summer and winter values of Mg was significantly higher as compared to the other parameters.

3.2.4 Hardness

Total hardness was employed here that defined as the molar concentrations of all multi-valent cations in water but primarily Ca and Mg (Qureshimatva *et al.,* 2015) and estimated by the following equation as suggested by WHO (APHA, 2017): Hardness, mg equivalent $CaCO_3$/L = 2.497 [Ca, mg/L] + 4.118 [Mg, mg/L]. Mean value of total hardness was ranged between 11.65-12.81 mg/L in summer and 10.92-11.51 mg/L in winter in this study.

Since the values were far below from 50 mg/L, the water in Cardiff Bay is soft, according to both Scottish Water (2020) and US Geological Survey (2020). A general increasing trend was observed, although marginal, from 2003 onwards where the maximum value was recorded in summer 2005. The slight increase of hardness in summer was probably due to the increased dissolution of Ca and Mg minerals by elevated temperature. In terms of monitoring sites, the mean concentration for latter sites (15-19) was much higher than that of earlier sites (1-10), especially in winter. Hence, water in the Taff was concluded to be softer than in the Ely.

3.2.5 Cl

The average chloride concentration in Cardiff Bay was found 3.546 mg/L in summer and 3.278 mg/L in winter. A decreasing trend in mean Cl was observed in initial seasons, followed by a steady unchanged pattern. The difference between summer and winter mean values in 2001 was significantly varied, more than 20%. Apart from the conversion of freshwater environment, another reason might be the dilution of lake water by heavy rain. Cl might inversely affect BOD by killing or inhibiting the microorganisms that decompose organic matter in water (Islam and Chowdhury, 2020) and this fact validated the increasing trend of BOD in Cardiff Bay water. Site 15 had significantly higher values of mean Cl, both in summer and winter, as compared to the other sites.

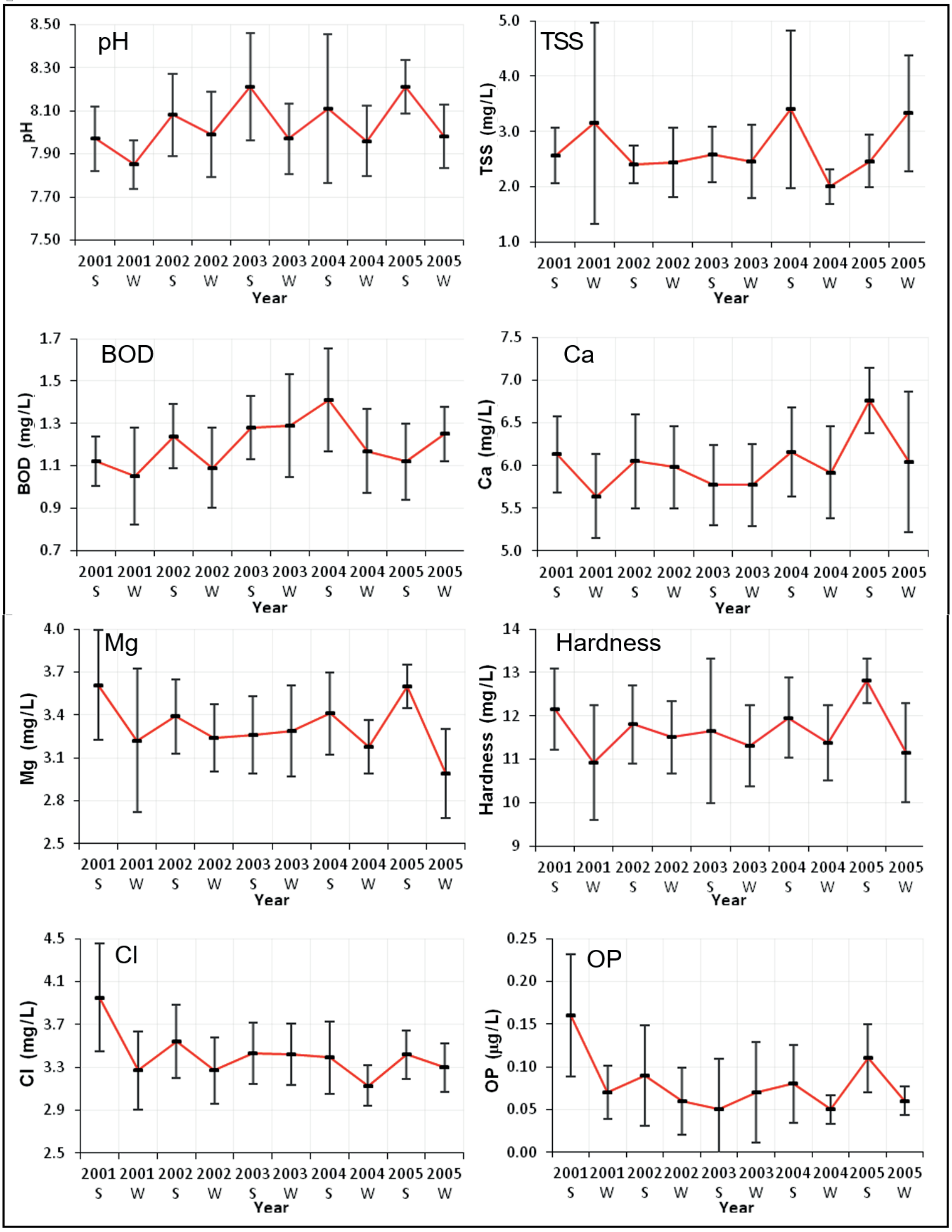

Figure 2. Plots of the parameters as a function of time (95% CI for the mean)
[Standard error of the mean]

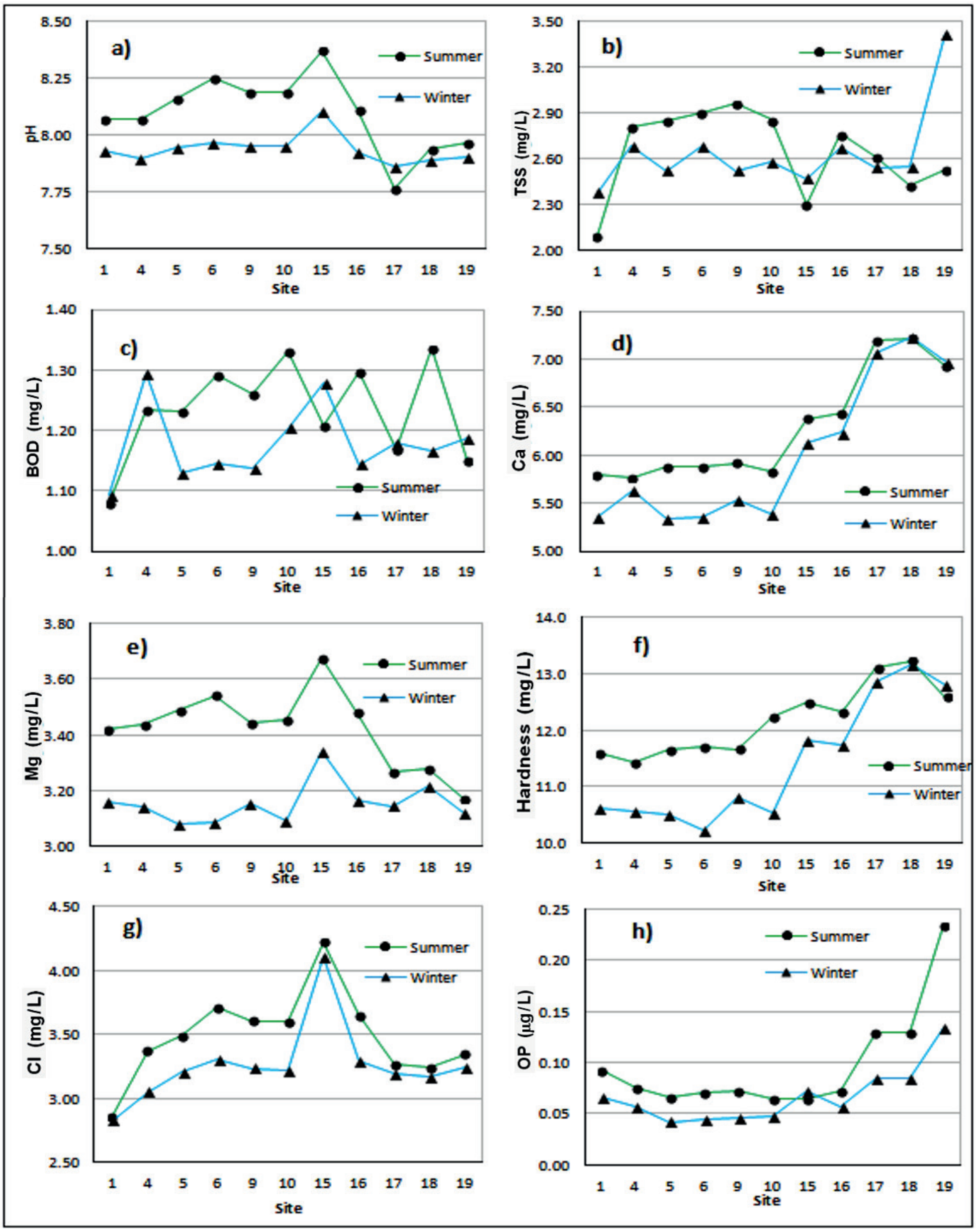

Figure 3. Plots of the mean parameter vs site for different seasons [plots of a, b, c, d, e, f, g and h represent pH, TSS, BOD, Ca, Mg, hardness, Cl and OP respectively]

3.2.6 TSS

Total suspended solids are organic and inorganic solid materials of size larger than 2 µm, which remain suspended in water. These include silt, planktonic algae, agricultural runoff, industrial wastes, fine debris and other particulate matters. No clear pattern of TSS was observed in the study. Mean TSS was found to be consistent till summer 2004 where a significant increase in the value, 3.40 mg/L, was noticed. Following that, the mean value was drastically decreased to 2.0 mg/L in winter months for that particular year. Mean TSS was spatially homogeneous throughout the lake system except for sites 1 and 19, which showed significantly lower and higher values respectively. These two sites were situated away from main body of the lake, at the Taff and Ely respectively.

3.2.7 OP

Orthophosphate (PO_4^{3-}), or soluble reactive phosphate, is an essential nutrient for all organisms, and is common in soils, rocks and sediments (US Geological Survey, 1992). But excessive orthophosphate in surface water bodies could lead to eutrophication, causing algal and cyanobacterial blooms, biomass production of phytoplankton and macrophytes (WHO, 2017; FAO, 2020) and hence reduces dissolved oxygen. European Union (2019) has set a guideline value for total phosphorus (P) up to 25 µg/L, whereas orthophosphate ranges about 10 µg/L among unpolluted rivers (Wetzel, 2001). It was observed that OP concentration was temporarily homogeneous throughout Cardiff Bay within the range of 0.05 - 0.16 µg/L, indicating that it demanded supplement OP as a nutrient. The concentration level was mostly unchanged for sites 1-16, but an increasing trend was observed for the sites 17, 18 and 19.

3.3 Inter-Parameter Correlations and Season-Site Interactions

Pearson correlation coefficient (r) was estimated to test the degree of relationship among the parameters. The correlation among the selected parameters were analyzed and represented in Table 2. The parameters showed some degree of correlation among themselves, however, majority of them showed significantly positive correlations at $P < 0.0001$ level. BOD showed a negative correlation with hardness and Ca, while the remaining parameters were positively correlated.

Table 3 provided sources of variation in different parameters using general linear model where interactions between seasons and sites were assessed. Significantly higher ($P < 0.05$) P value was obtained for pH, then for BOD ($P < 0.01$); while P value was calculated to be 0.001 for hardness, Cl, Ca and Mg.

Table 2: Matrices of Pearson's correlations between transformed physico-chemical variables

Variables[a]	pH	BOD	Hardness	Cl	Ca
BOD	0.317***				
Hardness	0.371***	-0.032			
Cl	0.410***	0.433***	0.433***		
Ca	0.296***	-0.047	0.807***	0.348***	
Mg	0.532***	0.004	0.720***	0.644***	0.571***

[a] Significance levels: *P < 0.05; **P < 0.01; ***P < 0.0001

Table 3: Season-Site Interactions. Significance levels: *P < 0.05; **P < 0.01; ***P < 0.0001

Variable	pH	BOD	Hardness	Cl	Ca	Mg
F value	1.31	1.39	2.23	6.02	4.01	1.85
P value	0.031*	0.012**	0.001**	0.001**	0.001**	0.001**

3.4 Comparison with Other Artificial Freshwater Lakes

A comparative study was conducted to assess the water quality of Cardiff Bay against the relevant data obtained from three different man-made freshwater lakes situated in Ghana, Nigeria and Malaysia. The comparison is presented in Figure 4. The values of pH ranged from 6.63 (Cempaka Lake) to 8.29 (Strabag Lake). The BOD and Mg values were marginally high at Volta Lake whereas TSS was higher at Cempaka Lake. Significantly increased values of hardness, Ca, Cl and OP were observed at Strabag Lake as opposed to the other ones. The values of hardness and Ca at Strabag Lake were found to be 94.27 mg/L and 33.22 mg/L respectively. Kannan (1991) classified water based on hardness as soft, if hardness value lies between 0-60 mg/L and moderately hard for 61-120 mg/L.

International regulation (e.g., EA, USEPA etc.) varies from regions to regions. However, comparison of the selected parameters (Olalekan *et al.,* 2015; Amoo and Komolafe, 2018; Aziz *et al.,* 2017) lead to the following order according to water quality: Cardiff Bay > Cempaka Lake > Volta Lake > Strabag Lake. The water in Cardiff Bay was found to be the best among them for several reasons. Although the water was slightly alkaline in nature (Merrix-Jones *et al.,* 2013); it was relatively soft (Hand, 2004), transparent, comparatively aerated and has little chance of causing eutrophication, if not amended. All the studied water quality parameters of Cardiff Bay were within the acceptable limits of EU (2019) and USEPA (2002).

3.5 Future Trend Analysis

The future trend, up to 50 years, has been analyzed using CurveExpert Professional software. The models that fit the data with good r values and less standard errors, s were considered. The best-fitted models were Rational, Exponential Association 2 and 3, Harmonic Decline, Ratkowsky and Bleasdale. The details of each of the models with related parameters were shown in Figure 5. In 2020, the future trend of parameter pH was cross-checked with recent data available in Hydrosphere website (Cardiff Harbour Authority, 2020). The percentage difference between actual pH (8.041) and model pH (8.035) was only 0.07%, which validated the model. It is to be mentioned that to validate the future prediction accurately, site-specific calibration is required considering the variables concerned.

The future trend showed that pH, Mg, Cl and OP should decrease; TSS and BOD should increase to a little extent, while Ca and hardness should be almost unchanged with course of time. After 50 years, according to the models, the values of pH, TSS, BOD, Ca, Mg, hardness, Cl and OP would be 7.92, 2.75, 1.23, 6.02, 3.29, 11.67, 3.21 and 0.05 units respectively. Hence, the overall water quality of Cardiff Bay would not deteriorate, if not better, in future as equilibrium would be established.

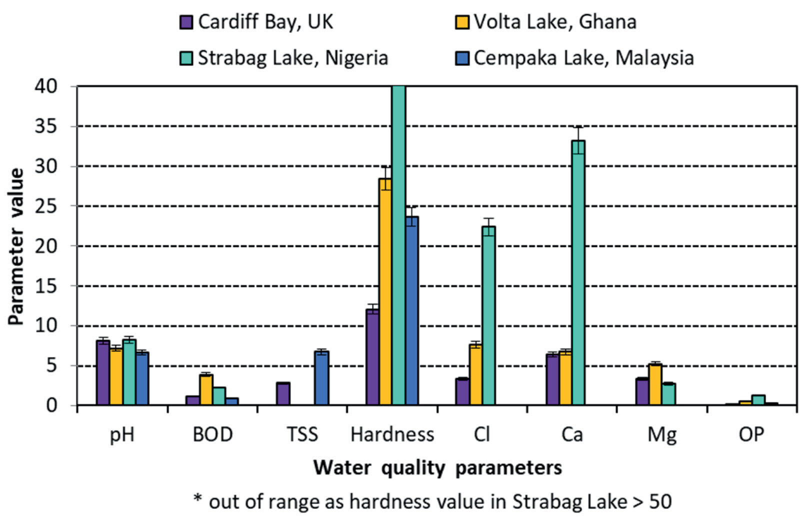

Figure 4. Comparison of the selected water quality parameters with several artificial freshwater lakes

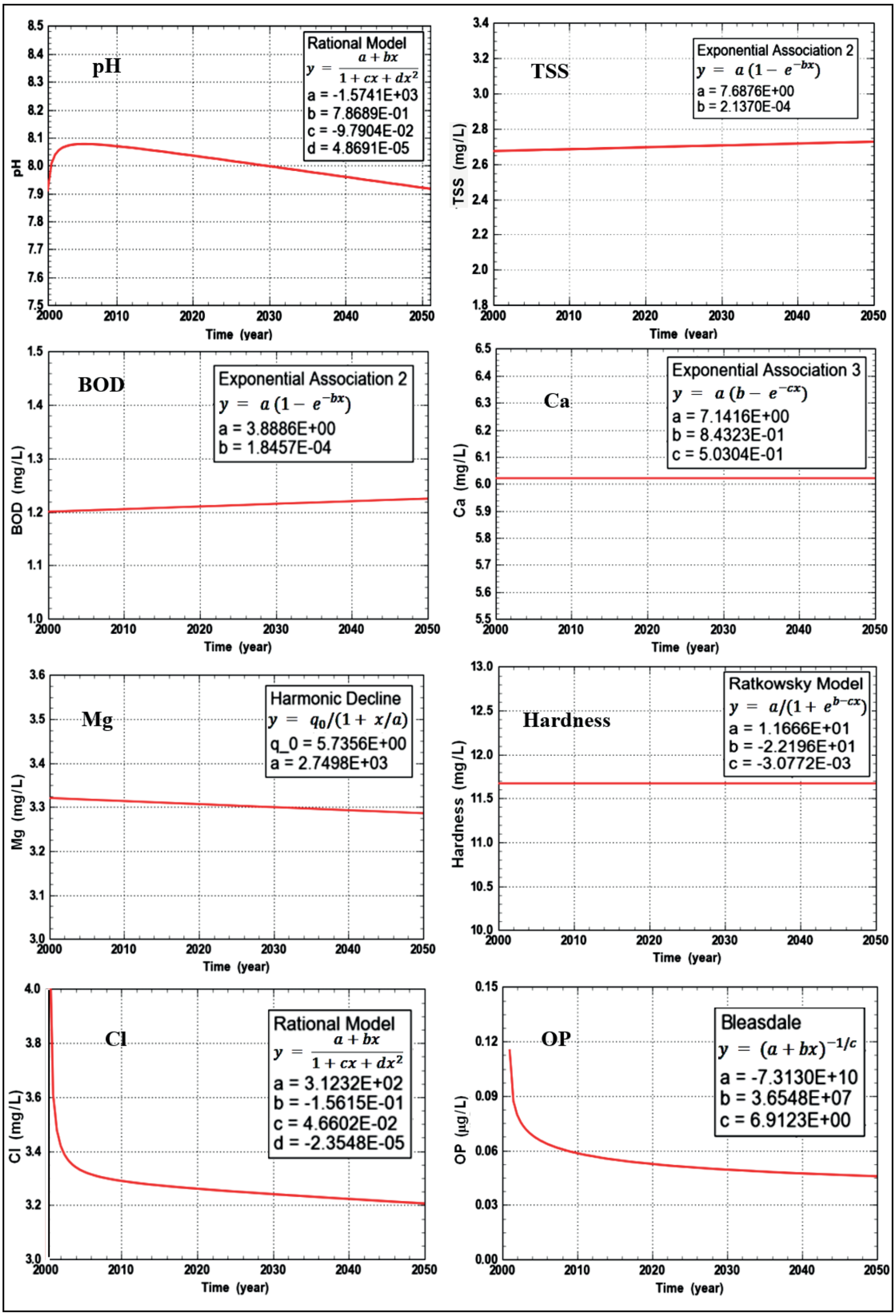

Figure 5. Prediction of water quality of Cardiff Bay over 50 years

Cardiff Bay is a relatively recent formation in comparison to the other artificial impoundments considered in this study. Water quality must be strictly maintained to meet the relevant standards so that aquatic lives can thrive and people can enjoy a wide variety of recreational activities by keeping pollution level under control. Any potential changes in the lake system are likely to affect entire water chemistry, some more significantly than others, since all aspects of lake water chemistry are interrelated (Wetzel, 1983). Variation of lake depth could identify any correlation between lake level and concentrations of water chemistry parameters, especially TSS.

4. Conclusion

This study investigated the water quality of Cardiff Bay by analyzing several parameters for seasonal and site-specific variation. Analysis of historic data provided a benchmark to predict future water quality. The overall findings of this study are:

• The results indicated that water quality in Cardiff Bay varied from little to moderately during five years of the study.

• The bay water was found mildly alkaline and relatively soft with respect to seasons and sites within the study period.

• Mean values of the parameters were mostly observed higher in summer as compared to winter, especially in 2001.

• Spatial pattern was inconsistent as site-specific variation was more prominent. It was observed that the differences of concentration levels of the studied parameters were maximum between the mouths of the Taff and Ely. In most cases, higher values were detected in the Taff.

• The overall trend also suggested that inter-annual variation was small and insignificant.

• The correlation among the selected parameters indicated that majority of them were positively correlated ($P < 0.0001$) except BOD which showed a negative correlation with hardness and Ca.

• While assessing the interactions between seasons and sites, the significantly higher ($P < 0.05$) P value was found for pH, then for BOD ($P < 0.01$).

• A comparative study was carried out which suggested that water in Cardiff Bay is generally safe and within the recommended limit of freshwater and similar lakes around the world.

• A future trend analysis was performed for extrapolating data up to 50 years and validated for pH with good agreement.

• Continuation of further investigation of the data is required for effective monitoring to control anthropogenic activities and predict future direction with better accuracy.

Acknowledgements

The authors would like to take this opportunity to express their gratitude to CHA for providing water quality data of Cardiff Bay. Sincere appreciation is conveyed to Catchment Research Group, Cardiff University, UK, especially to Professor Dr. Steve J. Ormerod and Dr. Faye L. Merrix-Jones, for their support provided to data collection and interpretation.

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