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Physico-Chemical Dynamics and Water Quality Assessment of Drigh Lake, Sindh, Pakistan

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ABSTRACT

This study assesses the seasonal dynamics of physico-chemical parameters and evaluates the water quality status of Drigh Lake to understand its ecological condition and eutrophication risk. Seasonal water samples were collected from multiple stations within the lake and its inlets, and key parameters including temperature, pH, dissolved oxygen, transparency, total suspended solids, and total dissolved solids were analyzed using standard field and laboratory methods. The results revealed pronounced seasonal variability across all parameters, with elevated temperatures, reduced dissolved oxygen, and lower transparency during summer months, indicating intensified biological activity and organic matter decomposition. Higher suspended solids and dissolved solids during periods of low water level highlighted the strong influence of agricultural runoff and evaporation-driven concentration effects. Although most parameters remained within national and international permissible limits, the observed trends reflect progressive nutrient enrichment and increasing eutrophication pressure. The findings demonstrate that watershed-driven inputs, combined with shallow lake morphology and seasonal hydrological fluctuations, are key drivers of water quality degradation in Drigh Lake.

Keywords: *Drigh Lake, Water Quality, Physico-chemical Parameters, Seasonal Variation, Eutrophication, Wetland Management.*

Citation: APA

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Introduction

Freshwater lakes form part of the inland water ecosystem and are very important in regulating the ecological functions, sustaining the biodiversity and human livelihoods. Sindh province in Pakistan is blessed with a number of perennial freshwater lakes, which have strong connections with the indus river system and they are Keenjhar Lake, Haleji Lake, Manchhar Lake and Drigh Lake (Arain et al., 2008; Mahar et al., 2000). Not only are these lakes a source of water and fisheries, but also the major wetlands to migratory birds and aquatic plants and animals. Nevertheless, growing human activities in these freshwater systems, including agricultural activities, water diversion, nutrient enrichment, and climate fluctuations have led to the progressive degradation of water quality in most of these freshwater systems (Gupta, 2000; Kant & Vohra, 1989). Consequently, physico-chemical character evaluation has gained high importance in the systematic evaluation of the health of lakes, ecological risks, and sustainable management. Drigh Lake is an ecologically important wetland of the Sindh and is situated in Qambar Shahdadkot District around 18 km northwest of Larkana city. This lake spans a total of approximately 182 hectares (450 acres) and has a mean depth of 10 m and is almost 50m above the mean sea level. Geographically, the lake is located at the latitude of 27 deg 34 and a longitude of 68 deg 06 and the lake was formed due to flooding activities that were witnessed in the late nineteenth century. Monsoon rain, small streams, canal seepage and surface runoff of the adjacent agricultural lands (especially rice paddies) are the major sources of water that feed the lake (Mastoi et al., 2008; Arain et al., 2008). Figure 1 and Figure 2 depict the site and geographical area of the lake. As a result of its ecological significance, Drigh Lake was proclaimed a Wildlife Sanctuary in 1972 and as a Ramsar site in 1976, which is a crucial habitat of resident and migratory water birds (Ramsar Convention, 2018).

Figure 1: *Drigh lake location*

Figure 2: *Drigh Lake is apparent near Kirthar Mountains in the province of Sindh, Pakistan*

Lakes are dynamic systems of interaction of physical, chemical, and biological processes in a limnological perspective. Aquatic productivity, species composition, and ecosystem stability are controlled by physico-chemical parameters like the water temperature, pH, electrical conductivity, total dissolved solids, dissolved oxygen, alkalinity and nutrient concentrations (Scheffer, 1997; Smith et al., 2005). The effects of seasonality on temperature affect water density and stratification that regulate vertical mixing, distribution of oxygen and nutrient cycling in the water column (Bohacs et al., 2000). The dependence of temperature on density that supports the thermal stratification processes is depicted in Figure 3, and the formation of epilimnion, metalimnion, and hypolimnion in summer is depicted in Figure 4. These physical processes are especially significant in shallow lakes like Drigh Lake, where the changes in seasons may quickly change the ecological conditions.

Figure 3: *(Density and temperature relationship for distilled water)*

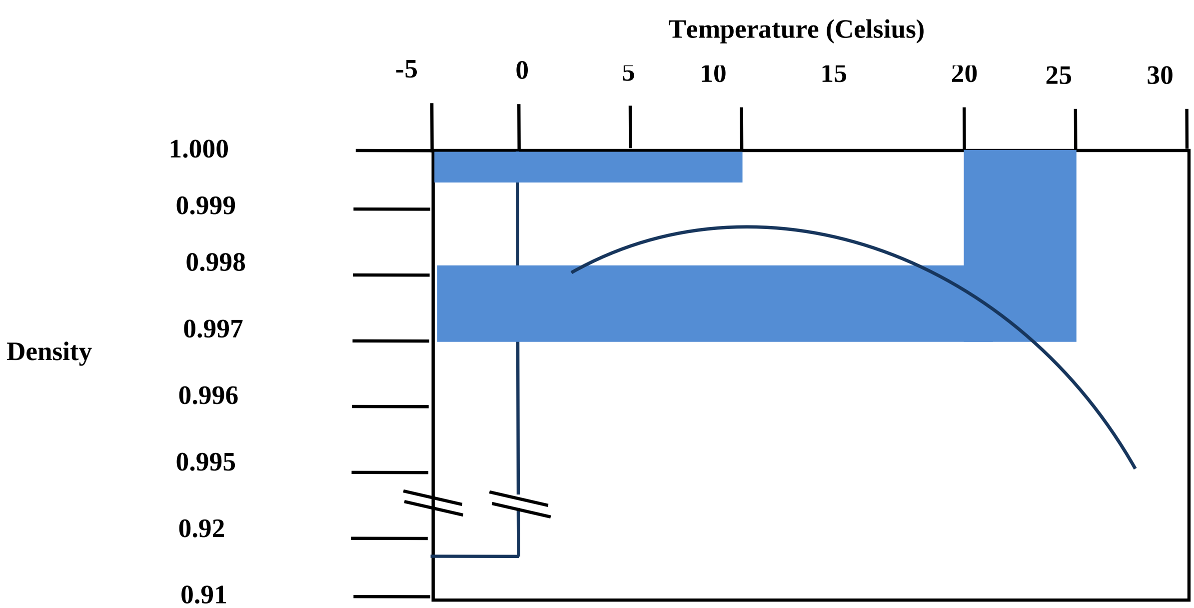
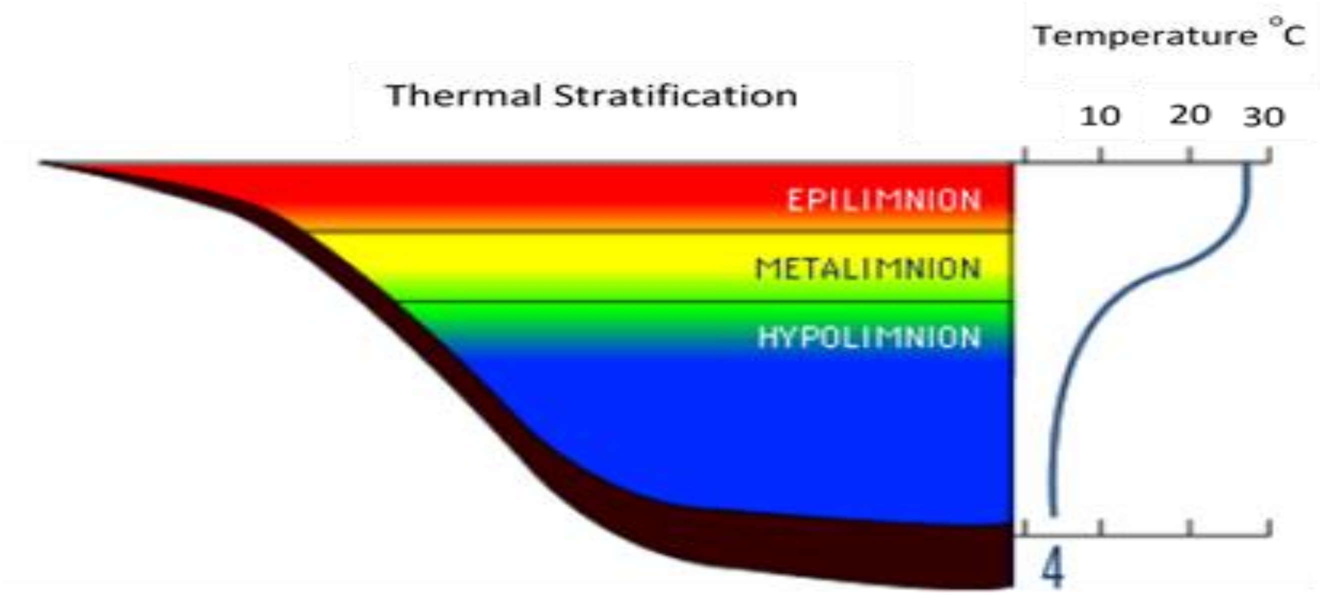


Figure 4: *(Thermal stratification)*



The other important physical parameter that determines primary productivity in freshwater lakes is light penetration. The intensity of light penetration defines the depth of euphotic zone, where photosynthesis is possible, and has a direct impact on the growth of phytoplankton and macrophytes (George, 1968; Verma et al., 1978). Lack of transparency due to an abundance of turbidity or algal blooms inhibits the photosynthetic activity and can shift the food web. The correlation that exists between the light penetration and the water clarity. Transparency changes are also often associated with human actions in the watershed, especially runoff of agricultural products and soil erosion. The area around Drigh Lake is densely agricultural and storm water run-offs associated with the agricultural activities bring nutrients and suspended solids to the lake. Table 1 and Table 2 are conceptual representations of the effects of land use and watershed properties on nutrient loading.

Table 1: *(Phosphorus export coefficients)*

	Phosphorus (kg/km2yr)		
	HIGH	**MID**	**LOW**
Urban	500	80-300	20
Rural/Agriculture	300	40-170	10
Forest	45	14-30	02
Precipitation	60	20-50	15

Over the past few decades, the Drigh Lake has undergone a steady environmental degradation process which has been mainly caused by human-induced disturbances and change in hydrological regimes. The floodwater that is diverted to irrigation has decreased the area of water spread on the lake whereas the constant inflow of nutrient-laden agricultural runoff has intensified the process of eutrophication (Kazi et al., 2009; Mahar et al., 2009). Higher levels of nitrogen and phosphorus boost uncontrolled proliferation of phytoplankton, decrease the transparency of water and cause an increase in biological oxygen demand, which in most cases causes depletion of oxygen and stress to aquatic life (Vollenweider, 1971; Boyd and Tucker, 1998). The occurrence of seasonal thermal stratification also adds to the depletion of oxygen in deeper levels during summer further limiting habitats of fish and other aerobic organisms (Kramer, 1987; Poehlmann, 1989). Nutrient enrichment, decreased mixing and decreasing water levels have profoundly changed the ecological balance of Drigh Lake where the effects are easily observed through fish productivity and water birds' population.

Table 2: *(Presence of phosphorus at various sectors).*

Forest	4.5 kg phosphorus
Rural/Agriculture	30.0 kg phosphorus
Urban	50.0 kg phosphorus

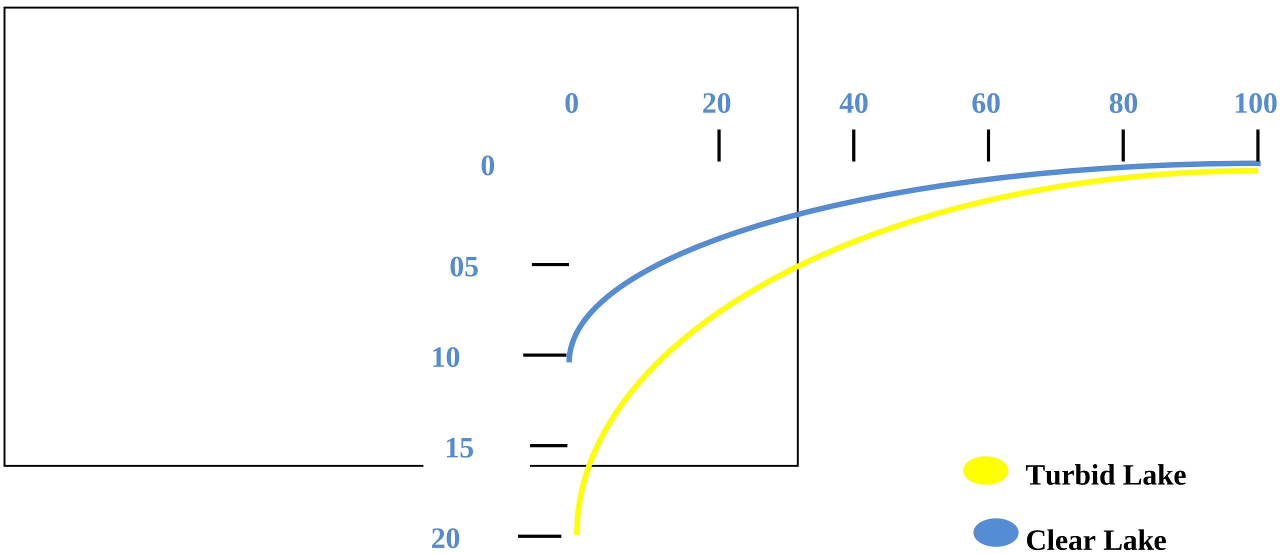
Since Drigh Lake has ecological significance, and the pressure on it is growing, it is vital to analyze seasonal changes in physico-chemical parameters in detail. Seasonal monitoring enables the determination of periods of significant environmental stress, assessment of risk of eutrophication and the determination of relationships between watershed processes and in-lake water quality dynamics (Harris, 1986; Nazneen, 1980). These kinds of assessments give a scientific rationale to the conservation of wetlands, sustainable water management and policy interventions to protect the Ramsar-designated sites. The given study provides a complete assessment of the water quality conditions in the Drigh Lake and helps to make informed decisions regarding the long-term sustainability of the given freshwater wetland, based on seasonal changes in the major physico-chemical parameters and their interpretation in the ecological perspective.

Literature Review

2.1 Studies on Phytoplankton of Aquatic Ecology and Limnology

The continuous focus of limnological research has been on the fact that phytoplankton communities are very sensitive to water quality and ecological status of freshwater systems. Alterations in physico-chemical parameters like temperature, dissolved oxygen, availability and unavailability of nutrients and transparency have direct effects on the composition, abundance and seasonal succession of phytoplankton populations (Nazneen, 1980; Harris, 1986). Initial research indicated that the phytoplankton biomass is sensitive to the variation in the nutrient levels, especially nitrogen and phosphorus and thus phytoplankton is a sensitive indicator of the eutrophication process in lakes (Vollenweider, 1971; Dillon, 1974). A number of regional studies carried out in Sindh and other areas in Pakistan give solid empirical evidence to the association between physico-chemical conditions and aquatic productivity. Mahar et al. (2009) also recorded the seasonal changes in phytoplankton and chlorophyll content in Manchhar Lake with high chlorophyll-a concentrations in seasons when nutrient levels were high. The same results were provided by Mahar et al. (2005), who noted that the input of organic matter and the decomposition of plant debris had a great influence on algal diversity and fish population in Manchhar Lake. All these studies imply that nutrient enrichment, especially in agricultural runoff, has a dominant role in the development of phytoplankton in shallow freshwater lakes. Temperature is found to be a major control of phytoplankton growth and seasonal succession. Nazneen (1980) and Mehboob and Shery (2001) indicated that increased temperatures of water in summer seasons boost metabolism and also support growth of specific algal groups especially Cyanophyceae. On the other hand, Kruger (1997) has proved that thermal discharges leading to sudden rise in water temperature can cause disturbance in planktonic communities and lower the species diversity. Stratification and mixing of water due to temperature have also been associated with seasonal dominance of phytoplankton thus affecting nutrient distribution in the water column (Keeler et al., 1999). Phytoplankton productivity is also controlled by the availability of light and transparency of water. The less visibility of the Secchi disk which is frequently linked to higher turbidity or algal proliferation has been demonstrated to restrict light penetration and modify photosynthetic efficiency (Verma et al., 1978; George, 1968). In Drigh Lake, the association among light penetration and lake productivity is conceptually depicted in Figure 5 that emphasizes the limitation of the depth of the euphotic zone by the height of turbidity. Similar results were obtained in studies by Singh and Singh (1995) and Kumar and Singh (1994), in which turbidity caused by untreated wastewater and runoff largely influenced the density and composition of phytoplankton. Repeatedly the nutrient enrichment and in particular the phosphorus loading has been found to be the driving force of eutrophication in freshwater lakes. The relationship between phosphorus input and the lake trophic status was founded by Vollenweider (1971) and the one between phosphorus levels and chlorophyll was showed to be strong by Dillon (1974). These results have been supported by local research in Sindh which demonstrated that organic pollution and agricultural drainage increase the nutrient levels and encourage uncontrolled growth of algae (Abbasi et al., 2007; Mahar et al., 2004). The processes eventually cause depletion of oxygen and degradation of habitats hence the need to monitor nutrient dynamics of lakes like the Drigh Lake.

Figure 5: *(Light versus depth profile for a clear and turbid lake)*



2.2. Ecology and Diversity of Aquatic Birds in Drigh Lake

Stable water quality and sufficient biological productivity in wetlands are important to support the resident and migratory water birds. Drigh Lake has been known to be a significant wetland ecosystem and is also the habitat of a large variety of aquatic avifauna, the abundance of which is directly related to the depth of the water, the quality of the water, and the availability of food. The ecological significance of the wetland is also evident in the number of water bird species documented in Drigh Lake between 2009 and 2013 (38 species of water birds) that are both resident and migratory species, signifying the ecological significance of the wetland at the regional and international levels. The change in the hydrological and physico-chemical conditions has been proven to be very similar to seasonal variations in the population of the birds at Drigh Lake. The highest migration bird counts were observed in winter months especially in months of November to January when the water level and temperature were favorable to food and rest (Jehangir et al., 2000). A summary of the seasonal appearance of aquatic birds is presented in Table 3 that demonstrates apparent differences in the presence and absence of birds during spring, summer, autumn, and winter.

Table 3: *Seasonal Status of Some Common Water Birds of Drigh Lake*

Scientific Name	Common Name	Status
Anas clypeata	Shoveller	Migrant
Aythya ferina	Common Pochard	Migrant
Anas crecca	Common Teal	Migrant
Phalacrocorax niger	Little Cormorant	Resident
Anas platyrhynchos	Mallard	Migrant
Anas acuta	Pintail	Migrant
Tachybaptus ruficollis	Little Grebe	Resident
Amauronis phoenicurus	White Breasted Water Hen	Resident
Fulica atra	Common Coot	Migrant
Phalacrocorax carbo	Large Cormorant	Migrant
Phalacrocorax niger	Little Cormorant	Resident
Anas platyrhynchos	Mallard	Migrant
Anas strepera	Gadwall	Migrant
Nycticorax nycticorax	Night Heron	Resident
Egretta garzetta	Median Egret	Resident
Ardeola grayii	Pond Heron	Resident
Himantopus himantopus	Black-winged Stilt	Resident
Actitis hypoleucos	Common Sandpiper	Resident

The decrease in the population of the aquatic birds of Drigh Lake has been noted to be caused by water quality degradation. Low oxygen dissolution, high turbidity and excessive development of emergent vegetation reduce food availability and appropriate habitat of most species (Poehlmann, 1989; Boyd and Tucker, 1998). Table 4 shows the diversity and abundance of species of birds recorded at Drigh Lake compared to the global and regional levels. These comparisons put a focus on the ecological importance of Drigh Lake as well as underscoring the susceptibility of the avifaunal diversity of the lake to environmental degradation. The data of long-term monitoring also shows that there is a decreasing tendency in the bird population, especially among the winter migrants like Common Coot, Shoveler and Northern Pintail. Precise records of ducks and other waterfowls registered between 2009 and 2013. Such data show that there is a large variation in interannual variability and the overall decrease in population sizes due to the deterioration of water quality, the destruction of habitats, and human disturbances.

Table 4: *Number of Species of Water Birds Recorded Worldwide*

World	Asia	India	Pakistan	Sindh	Drigh Lake
767	328	245	192	131	44

2.3. Water Birds Present at Drigh Lake

In-depth species abundancy evaluation at the species level indicates that Drigh Lake has a rich population of aquatic birds, such as ducks, herons, egrets, cormorants, and waders. Physico-chemical conditions, especially water depth, transparency, and presence of aquatic vegetation have a potent effect on the occurrence and abundance of these species. Others like Mallard, Gadwall, Common Pochard and Northern Shoveler tend to inhabit open water that is sufficiently deep whereas herons and egrets are usually found in shallow and vegetated areas. The relative abundance of resident and migratory birds at Drigh Lake indicating the pre-eminence of migratory species in winter. The seasonal changes in the occurrence of birds as recorded by systematic visual surveys point to water birds being very sensitive to seasonal drying, water diversion and water quality changes. In low water level seasons especially during late summer, most species either move to the adjacent wetlands or move to the agricultural fields. The anthropogenic stressors, such as nutrient enrichment, siltation, encroachment, and indiscriminate harvesting of macrophytes have been the major factors that have changed the habitat structure of Drigh Lake. Such developments have decreased the nesting places and feeding areas of aquatic birds, which has led to the reduction in the richness and abundance of species. The most common bird species observed in the, and long-term changes in population of the major species are presented in Table 5. The degradation of water quality and its influence on the health of avifauna are highly correlated, which is highlighted by the steady decrease that has been detected in numerous species.

Table 5: *Water Birds Population and Their Status at Drigh Lake*

Common Name (Scientific Name)	Mean	SD
Gadwall (Anas strepera)	430	63.48
Common Coot (Fulica atra)	1935	276.57
Night Heron (Nycticorax nycticorax)	887	277.68
Common Teal (Anas crecca)	2390	108.91
Mallard (Anas platyrhynchos)	97	11.17
Northern Pintail (Anas acuta)	177	30.38
Shoveler (Anas clypeata)	1680	101.18
Garganey (Anas querquedula)	6	1.58
Common Pochard (Aythya ferina)	40	11.89
Indian Pond Heron (Ardeola grayii)	17	4.15
Grey Heron (Ardea cinerea)	25	6.54
Little Egret (Egretta garzetta)	18	5.40
Median Egret (Mesophoyx intermedia)	19	4.82
Large Egret (Egretta alba)	43	8.11
Herring Gull (Larus argentatus)	44	7.60
Black-headed Gull (Larus ridibundus)	34	10.73
Great Cormorant (Phalacrocorax carbo)	39	9.70
Little Cormorant (Phalacrocorax niger)	6	3.81

2.4. Watershed Influence, Stormwater Impact, and Nutrient Loading

Lake watershed is a crucial factor in defining the quality of the water in a lake since it regulates the volume and quality of water, sediments, and nutrients entering a lake. The area of Drigh Lake is highly susceptible to surface runoff of nutrients because of the intensive farming activities. The theoretical connection that exists between watershed area and nutrient runoff that illustrates how augmented runoff leads to deteriorating water quality. Phosphorus has been singled out as the most vital nutrient that determines primary productivity in freshwater lakes. Table 6 gives export coefficients of phosphorus by various land uses and Table 7 shows that agricultural and urban land make much more phosphorus than forested land. These results are in line with previous research conducted by Reckhow and Simpson (1980) that demonstrated conversion of natural land to agriculture has a significant nutrient loading effect and a large-scale acceleration of the eutrophication process.

Table. 6: *Phosphorus Export Coefficients*

	Phosphorus (kg/km2yr)		
	HIGH	**MID**	**LOW**
Urban	500	80-300	20
Rural/Agriculture	300	40-170	10
Forest	45	14-30	02
Precipitation	60	20-50	15

Storm water also contributes to the reduction of water quality by carrying suspended solids, nutrients, and contaminants to the lake. High levels of turbidity decrease penetration of light, interfere with photosynthesis, and alter thermal structure which eventually influences biological communities. The combination of watershed events, seasonal weather fluctuations, and other human activities describes the necessity of integrated water quality evaluation and management in Drigh Lake.

Table 7: *Presence of Phosphorus at Various sectors*

Forest	4.5 kg phosphorus
Rural/Agriculture	30.0 kg phosphorus
Urban	50.0 kg phosphorus

Research Methodology

Study Area

The current research was carried out in Drigh Lake which is a historic freshwater wetland in Qambar Shahdadkot District, Sindh, Pakistan. The lake has an approximate latitude of 27deg34' N and a longitude of 68deg02' E and it is located some 18 km northwest of the Larkana city. Drigh Lake occupies an area of approximately 182 hectares (450 acres) and has an average depth of approximately 10 m in depth. The lake is semi-natural in nature and a little brackish in nature, and has vast marshlands which sustain a variety of aquatic vegetation. The lake is hydrologically fed mainly by monsoon rain, small streams flowing into it on the eastern side, seepage of the canals on the north and surface runoff on the farmlands around it especially rice paddies. The seasonal distribution of the water spread of the lake is determined by the intensity of rainfall and also water diversion to the irrigation needs. The climate of the area is an arid subtropical zone with hot summers and mild winters, and low yearly rainfall that occurs during monsoon seasons (Haq et al., 2012; Khan et al., 2013).

Sampling Design and Stations

In order to achieve representative characterization of the water quality of the lake, systematic sampling design was used. There were five sampling stations that were chosen in Drigh Lake and they covered various hydrological and ecological areas in the water body. Besides, two stations were chosen at inlet streams supplying the lake with water. Sampling stations were chosen according to the circulation of water, the closeness to inflow sources, the effects of agricultural runoff, and the change of vegetation cover. This is a spatial distribution of the stations that enabled measurement of the internal lake conditions and external inputs on the water quality. Sampling was done on a seasonal basis to ensure that a temporal variability was taken into consideration with regards to climatic conditions and hydrological changes.

Field Measurements

Key physico-chemical parameters that were directly measured in each sampling station were conducted in the field. A portable hand-held digital multiparameter (Hanna HI 88129) was used to measure water temperature, pH, electrical conductivity, salinity, and total dissolved solids using the right sensor. In situ measurements of the dissolved oxygen were done using standard methods of dissolved oxygen measurement to reduce the changes brought about by sample manipulation and transportation. Transparency of water was determined by means of Secchi disk in order to evaluate the depth of light penetration and the condition of relative turbidity in the lake. The measurements in the field were all done in the daytime to ensure uniformity in the sampling events.

Sample Collection and Preservation

Laboratory samples of water were taken in 0.75 dm3 capacity, pre-cleaned and capped polyethylene bottles. Sampling was done with caution not to contaminate the surface and disruption of the bottom sediments. The samples were collected and immediately put in dark containers to reduce photochemical reactions and biological activity. All the samples were taken to the laboratory and put through the procedure within six hours of collection to maintain their initial physico-chemical properties. To preserve the accuracy of the analysis, the standard preservation techniques were used where needed according to the established protocols.

Laboratory Analysis

Laboratory tests aimed at identifying major chemical parameters that would be pertinent in water quality and ecological evaluation. To determine the organic pollution and oxygen consuming potential of the lake water, biochemical oxygen demand and chemical oxygen demand were determined. Nutrient analysis was done to find out nitrogen species (nitrate and nitrite) and phosphorus which are key indicators of the potential of eutrophication. The major ions that included total hardness, total alkalinity, chloride, and others were also examined to determine the ionic composition and buffering capacity of the lake water. All of the analyses were performed according to the standard procedures, outlined in the Standard Methods of the Examination of Water and Wastewater (American Public Health Association) so that the methodology of the analysis is consistent and reliable (APHA, 1998).

Data Processing and Interpretation

The data collected were put in order of the season in order to study the changes of the physico-chemical parameters with time. The observed patterns were summarized in descriptive statistical methods by station of sampling and seasons. The effects of climatic conditions, hydrological inputs, and anthropogenic activities on the dynamics of water quality in seasons were compared. The results interpretation was based on the determination of the trophic condition of the lake, detection of eutrophication indicators, and interpretation of ecological consequences of physico-chemical changes. The parameters analyzed were assessed within the framework of the accepted limnological principles and the results reported in the past on freshwater lakes in Sindh and other similar areas.

Results

There was evident seasonal fluctuation of the physico-chemical properties of Drigh Lake during the study period. All of the measured parameters showed seasonal changes, as the overall effect of the climatic conditions, hydrological input, and biological activity. The findings below are presented in the following parameters to make it easier to understand the dynamics of time.

Water Temperature

Water temperature exhibited significant seasonal change, just after the ambient climatic conditions. Minimizing temperatures were noted at the time when it was winter and highest values were registered in summer. The average temperature rose consistently in the spring to summer and this was slightly reduced in the fall and significantly in winter. High temperatures in summer and low water levels with increased solar radiation were conditions characteristic of shallow freshwater lakes in dry areas.

Dissolved Oxygen

Temperature had an inverse relationship with dissolved oxygen levels in season. The highest level of DO was measured in winter and early spring but the level was relatively lower in summer months. This seasonal cycle indicates the higher oxygen solubility at lower temperature and higher photosynthetic rate at lower temperature. The low DO levels in summer are associated with elevated biological oxygen requirements and the high rate of respiration.

Water Transparency

Transparency showed clear seasonality with the highest values observed in spring and winter and lowest values in the summer and early autumn. Less transparency in the warmer seasons is linked with higher suspended solids, growth of algae and runoff that is turbid due to agricultural fields surrounding it. The seasonal changes in transparency show different conditions of light penetration which determine the primary productivity in the lake.

Hydrogen Ion Concentration (pH)

The Drigh Lake water was slightly alkaline and seasonal variation was moderate. The pH values were lower in spring and high in summer and autumn. The rises in pH seasonally are associated with a rise in photosynthetic activity that lowers the concentration of free carbon dioxide in the water column. The general pH was found to be within the range of values deemed as acceptable to freshwater biota.

Total Suspended Solids

There was a significant seasonal variation in total suspended solids, with higher values in summer and autumn, and lower values in winter. The high TSS during summer was associated with the high inflow of agricultural runoff and re-suspended bottom sediments because of low water depth. The seasonal change in the TSS had direct impacts on water transparency and nutrient transportation of the associated nutrients.

Total Dissolved Solids

Total dissolved solids had moderate seasonal variation where it was high in summer and winter and comparatively lower in spring and autumn. The increase in TDS in the summer corresponds to the effect of evaporation and a decrease in dilution whereas the increase in the winter corresponds to the decrease in biological uptake and concentration of dissolved ions. Even though there were seasonal changes in the values of TDS, they were within acceptable ranges of inland surface waters.

Table 8: *Seasonal Mean Values of Physico-Chemical Parameters of Drigh Lake (2012–2013)*

Season	Temperature (°C)	DO (mg L⁻¹)	Transparency (cm)	pH	TSS (mg L⁻¹)	TDS (mg L⁻¹)
Spring	19.67	9.55	160.29	7.85	30.04	1218.63
Summer	32.25	7.04	109.63	8.29	35.46	1264.14
Autumn	32.04	7.61	89.17	8.00	32.58	1146.51
Winter	23.42	8.99	89.67	8.71	28.08	1189.04

Discussion

The seasonal change in the physico-chemical parameters of the Drigh Lake represents the interaction of the climatic conditions, hydrological regime, and human activities in the watershed. The lake is a shallow freshwater wetland within a highly populated agricultural landscape and is therefore highly sensitive to external sources of nutrients and seasonal changes in water level. The parameter-wise analysis below discusses the observed trends in the context of eutrophication processes and watershed processes based on the known limnological principles and local empirical observations.

Temperature Dynamics and Ecological Implications

The change in water temperature in Drigh Lake was strongly linked to the ambient climatic conditions, and the highest value of water temperature was recorded in the summer season and lowest values in winter. This type of temperature regimes is common in shallow lakes of arid and semi-arid habitats where thermal buffering capacity is limited by lakes depth (Mehboob and Shery, 2001). High summer temperatures increase the metabolism of aquatic life and increase the rate of biogeochemical processes, such as nutrient mineralization and the breakdown of organic matter. These activities make nutrients more accessible in the water column hence causing the growth of phytoplankton and enhanced risk of eutrophication (Harris, 1986). Increased temperatures also lower the oxygen solubility, and this increases the impact of increased biological oxygen demand during high productivity periods. Other effects of temperature on the ecology of lakes have been reported in Manchhar Lake and Keenjhar Lake, where warming of the summer was linked to higher algal biomass and lower ecological stability (Mahar et al., 2009; Lashari et al., 2003). The observed temperature regime is therefore a major seasonal producer of eutrophic conditions in Drigh Lake especially when coupled with nutrient-rich inflows through the surrounding watershed.

Dissolved Oxygen and Organic Enrichment

Dissolved oxygen concentrations showed obvious seasonal changes, whereby the concentration was less in summer and higher in winter. This negative correlation with temperature is in agreement with the basic theory of limnology and indicates decreased oxygen solubility and increased biological oxygen requirements in the warmer months (Boyd and Tucker, 1998). In eutrophic systems, high nutrient level promotes phytoplankton explosion, which at the beginning generates oxygen by photosynthesis, but later causes oxygen depletion during night respiration and decomposition stages. In Drigh Lake, the decrease in the level of DO in summer is associated with the increased runoff and the inflow of organic matter by the surrounding paddy fields. This organic substance decomposes to use the dissolved oxygen, which may cause stressful environments to fishes and other aerobic organisms (Kramer, 1987). Similar results were present in a study by Larik et al. (2007), who found that there was low dissolved oxygen in fish pond with high organic loads. The observed seasonal reduction in the DO that is noted in the Drigh Lake thus points to progressive eutrophication that is caused by the enrichment of the watersheds with organic material.

Transparency, Suspended Solids, and Light Limitation

Seasonal differences in water transparency and total suspended solids give additional information on the process of eutrophication and the role of watersheds. Less transparency in the summer and early autumn periods indicates that there is a high density of suspended solids and phytoplankton, which reduces light penetration in the water column. High TSS of these seasons is mainly explained by stormwater runoff, soil erosion, and resuspension of the bottom sediments in the conditions of low water depth (George, 1968; Verma et al., 1978). The agricultural practices within the watershed are also significant in enhancing the importation of sediments and nutrients into the lake especially the irrigation processes and runoffs during the monsoons. The suspended particles do not only decrease the availability of light but also serve as vectors of phosphorus and nitrogen which strengthen the process of eutrophication (Vollenweider, 1971). In the lakes of Sindh and other parts of Pakistan, similar correlation in the turbidity, nutrient transport, and algal growth has been reported (Mahar et al., 2005; Abbasi et al., 2007). Reduced transparency, therefore, is a symptom and a strengthening loop of the eutrophic conditions in Drigh Lake.

pH Variation and Photosynthetic Activity

The Drigh Lake continued to be mainly alkaline throughout all seasons with the higher values being reported in the summer and autumn seasons. The rise in pH seasonally is usually linked with high photosynthetic rate where carbon dioxide is being extracted out of the water, causing a shift in the carbonate balance towards higher pH levels (Gupta, 2000). This effect is enhanced in eutrophic systems by the large algal concentration, especially when there is high light and temperature. Even though the measured pH values are in the ranges that are typically regarded as healthy to the freshwater organisms, the constant alkalinity may affect the nutrient availability, the solubility of metals, and species composition. Research studies by Khan and Ali

(2003) indicated a comparable seasonal rise in alkalinity, and pH both in monsoon and post-monsoon seasons associated with a rise in the inflow of nutrients and biological activities. The seasonal pH pattern in Drigh Lake also helps to justify the increased primary productivity and nutrient-based ecological change.

Total Dissolved Solids, Salinity, and Watershed Inputs

The total dissolved solids had moderate seasonal variation whereby there were higher concentrations in summer and winter. The high TDS levels in summer can be mainly explained by the effects of evaporation and low level of dilution in low water levels which is common in shallow lakes found in arid climates (Gupta, 2000). The increase in winter may indicate decreased biological uptake and dissolved ions concentration when there is no significant inflow. The agricultural runoff, the use of fertilizers, and the seepage of the canals into the watershed of Drigh Lake contribute significantly to the dissolved ionic load. The high TDS level though within allowable range in inland waters may affect osmotic stress among aquatic organisms and species composition over a period of time. The role of land-use practices in the development of lake water chemistry was also supported by Lashari et al. (2003) and Pirzada et al. (2011), who noted that the agricultural landscapes have increased dissolved solids in surface waters.

Integrated Eutrophication and Watershed Effects

The observed seasonal oscillations of physico-chemical parameters suggest that Drigh Lake is at the stage of nutrient enrichment and is moving to the eutrophic state. The morphology of the lake is shallow, the flushing capacity is low, and the lake is in close contact with highly cultivated agricultural lands, which increases the impact of external nutrient loading. The watershed contributes to phosphorus and nitrogen, which are carried by runoff and small inflow channels, which trigger primary productivity and initiate feedback processes of lower transparency, depletion of oxygen, and water chemistry changes. Such results are consistent with conceptual models of eutrophication suggested by Vollenweider (1971) and regional studies in Sindh, which highlight the role of watershed-based nutrients as the major cause of lake deterioration (Mahar et al., 2009; Abbasi et al., 2007). These processes are further subject to seasonal hydrologic changes that regulate the mixing, dilution and residence time. In the absence of proper watershed management and agricultural inputs control, the ecological status of Drigh Lake will continue to be worsened with negative implications on the aquatic biodiversity and wetland ecosystem services.

Conclusion and Policy Recommendations

Conclusion

The current paper offers an in-depth evaluation of the seasonal variations of the physico-chemical parameters in Drigh Lake and demonstrates the ecological significance of noted changes in the water quality. The findings indicate that temperature, the dissolved oxygen, transparency, pH, total suspended solids, and total dissolved solids are some of the major water quality indicators that strongly vary across seasons due to the influence of climatic conditions, hydrological variations, and anthropogenic stressors in the watershed of the lake. Being a shallow freshwater marshland in an arid area, Drigh Lake is sensitive to the external input of nutrients and the seasonal change in the water supply. The summer seasonal increase of temperature accompanied by a lowering dissolved oxygen and transparency indicate the high level of biological activity and organic matter degradation, which are typical of eutrophic freshwater systems (Harris, 1986; Boyd and Tucker, 1998). Enhanced suspended solids and dissolved ions in low water level and high agricultural activity periods are the additional evidence of the influential role of watershed-related inputs. Despite the fact that the majority of physico-chemical parameters were within the national and international allowable ranges, the tendencies that were observed are those of gradual nutrient enrichment and ecological stress, especially in summer and early autumn. Reduced transparency and seasonal oxygen depletion of the water coupled with alkalinity of the lake water indicates that under favorable conditions, primary productivity would be increased and phytoplankton would dominate. The results are also in line with the previous limnological researches done in freshwater lakes of Sindh, which have also reported similar relationship among nutrient loading, algal growth and deterioration of water quality (Mahar et al., 2005; Mahar et al., 2009). Taken together, the findings suggest a slow eutrophication process in Drigh Lake which is mainly caused by agricultural run-offs, changes in hydrological regimes, and the decrease in the dilution capacity. Since it is a Ramsar-listed wetland and a significant source of aquatic biodiversity and migratory water birds, the deterioration of water quality is a significant threat to the ecological quality and sustainability of Drigh Lake. Unless properly managed in a timely and effective manner, these pressures are bound to increase resulting in further degradation and loss of ecosystem services.

Policy Recommendations

Judging by the results of this research, a number of recommendations are offered based on the policy and management dimensions to preserve and recover the ecological well-being of Drigh Lake. To minimize the inflow of nutrients and sediments into the lake, first, watershed management is to be considered a priority. The surrounding catchment agricultural activities especially intensive paddy farming are contributing to nutrient loading by the runoff of fertilizers and suspended solids. External nutrient inputs can be greatly minimized through the encouragement of controlled fertilizer use, the use of buffer strip, and better drainage control, which would limit the process of eutrophication (Vollenweider, 1971; Abbasi et al., 2007). Second, the inflow of freshwater into the lake is necessary to preserve the water quality and ecological balance. Floodwater diversion and over-pumping of water to irrigate the fields have decreased the dilution capacity of the lake and increased the concentration effects of the lake during dry seasons. The policy needs to be aimed at controlling water abstraction and maintaining minimum environmental flow to maintain the hydrological regime of the lake especially during the critical summer seasons. Third, institutionalization of regular and systematic water monitoring should be created to monitor the seasonal and long-term changes in physico-chemical parameters. The continuous monitoring would enable the timely identification of the symptoms of eutrophication, adaptive management, and evidence-based decision-making. Majority of such monitoring programs must be in line with the national environmental standards and Ramsar wetland management guidelines. Fourth, water quality management should be incorporated into biodiversity protection in conservation strategies. The deterioration of water quality has a direct effect on fish populations and water birds' habitats, as well as on the latter, which require certain physico-chemical conditions to survive. Restoration initiatives, such as the controlled growth of the emergent macrophytes and shielding of open-water areas can augment the ecological resilience and enhance the suitability of habitats to the aquatic fauna (Mahar et al., 2009). Lastly, institutional coordination and community involvement is important to developing the Drigh Lake long-term sustainability. Sensitization of local farmers, fishers, and stakeholders can be used in awareness programs that are aimed at ensuring that the practices are environmentally friendly, and shared stewardship of the wetland is achieved. As Drigh Lake is a wetland of international importance, the cooperation of provincial environmental agencies, wildlife departments and conservation organizations is necessary to ensure that the integrated wetland management plans are implemented.

Conflict of Interest

The authors showed no conflict of interest.

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References

Abbasi, S. A., Abbasi, N., & Soni, R. (2007). Heavy metal contamination in aquatic ecosystems: A review. *Journal of Environmental Science and Engineering*, *49*(2), 85–98.

Arain, M. B., Kazi, T. G., Jamali, M. K., Jalbani, N., Afridi, H. I., & Shah, A. (2008). Physico-chemical characteristics of Manchar Lake water and their comparison with other global lakes. *Environmental Monitoring and Assessment*, *136*(1–3), 287–297.

Boyd, C. E., & Tucker, C. S. (1998). Pond aquaculture water quality management. *Springer*.

Dillon, P. J. (1974). A manual for calculating the capacity of a lake for development. *Ontario Ministry of the Environment*.

George, M. G. (1968). Comparative plankton ecology of five fish tanks in Delhi, India. *Hydrobiologia*, *31*(3), 353–373.

Gupta, P. K. (2000). Methods in environmental analysis: Water, soil and air. Agrobios.

Harris, G. P. (1986). Phytoplankton ecology: Structure, function and fluctuation. Chapman & Hall.

Jehangir, S., Mahar, M. A., & Lashari, B. K. (2000). Studies on avifauna of Drigh Lake, Sindh, Pakistan. *Pakistan Journal of Biological Sciences*, *3*(10), 1655–1658.

Kant, S., & Vohra, R. (1989). Physico-chemical characteristics of some freshwater bodies of Rajasthan. *Journal of Environmental Biology*, *10*(3), 203–208.

Khan, F. A., & Ali, S. (2003). Seasonal variations in physico-chemical characteristics of freshwater ponds. *Journal of Environmental Biology*, *24*(3), 253–258.

Kramer, D. L. (1987). Dissolved oxygen and fish behavior. *Environmental Biology of Fishes*, *18*(2), 81–92.

Larik, A. S., Mahar, M. A., & Lashari, B. K. (2007). Natural productivity of fish ponds in relation to physico-chemical parameters at Chilya fish hatchery, Sindh, Pakistan. Sindh University Research *Journal (Science Series)*, *39*(2), 87–94.

Lashari, B. K., Mahar, M. A., & Jahangir, S. (2003). Limnological studies of Keenjhar Lake, Sindh, Pakistan. *Pakistan Journal of Biological Sciences*, *6*(21), 1791–1794.

Mahar, M. A., Jahangir, S., & Lashari, B. K. (2005). Pollution indicators of algal flora of Nara Canal water entering Manchhar Lake. *Pakistan Journal of Biological Sciences*, *8*(9), 1253–1257.

Mahar, M. A., Jahangir, S., Lashari, B. K., & Sahito, A. R. (2009). Seasonal variation of phytoplankton and chlorophyll content in Manchar Lake, Sindh, Pakistan. *Pakistan Journal of Biological Sciences*, *12*(2), 102–108.

Mahar, M. A., Lashari, B. K., & Jahangir, S. (2004). Physico-chemical and biological studies of rainwater pools of Kohistan region, Sindh, Pakistan. *Journal of Biological Sciences*, *4*(2), 210–214.

Mehboob, S., & Shery, T. M. (2001). Relationship between water temperature and primary productivity in freshwater bodies. *Journal of Research (Science*, *12*(1), 45–52.

Nazneen, S. (1980). Influence of environmental factors on phytoplankton periodicity in freshwater lakes. *Hydrobiologia*, *72*(3), 249–255.

Pirzada, T. J., Shar, A. H., & Arain, M. B. (2011). Physico-chemical assessment of potable water quality of Khairpur city, Sindh, Pakistan. *Pakistan Journal of Analytical and Environmental Chemistry*, *12*(1–2), 6–12.

Scheffer, M. (1997). Ecology of shallow lakes. Chapman & Hall.

Smith, V. H., Tilman, G. D., & Nekola, J. C. (2005). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1–3), 179–196.

Verma, S. R., Sharma, P., & Tyagi, A. K. (1978). Studies on transparency and plankton productivity of freshwater ponds. *Indian Journal of Ecology*, *5*(2), 180–186.

Vollenweider, R. A. (1971). Scientific fundamentals of the eutrophication of lakes and flowing waters. *OECD Technical Report*.

World Health Organization. (1993). *Guidelines for drinking-water quality* (2nd ed.). WHO.

World Health Organization. (2001). *Guidelines for drinking-water quality* (3rd ed.). WHO.