Understanding the Variability in Estimation of Water Quality of Lakes and Reservoirs

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Abstract. This paper presents a critical review on the existing methodology of water quality assessment of lakes and reservoirs being used as a source of water supply and irrigation purposes. The seasonal and depth-wise variations in water quality are also analysed and presented through two case studies. It is inferred that water quality monitoring is a helpful tool not only to evaluate the impacts of pollution sources but also to ensure an efficient management of water resources and the protection of aquatic life. However, it is incomplete to make any meaningful prediction without correlating the prevailing catchment characteristics as well as imparting the scope for real-time action plan. The present study highlights a few strategic features causing variability in water quality and proposes a corroborative plan to address those issues.

1. Introduction

Surface water bodies are the most significant water resources for the municipal water supply. Nowadays it is wearisome to acquire clean water from the existing surface water resources [1]. Lakes and reservoirs are normally recognized as the integral components of the natural water cycle where storage of surface water is anticipated for delayed and controlled release for various consumptive and non-consumptive uses. As distinct based on their creation (natural versus man-made), the lakes and reservoirs are also remarkably critical in understanding the highly complex urban hydrology where safe and entrusted supply of drinking water is mandatory while maintaining the capacity to assimilate excess quantity (e.g. flash floods) and quality (e.g. release of pollutants to the environment). Unlike ephemeral channels, the lakes and reservoirs are characterized by well-defined storage capacity, controlled by the local geology and climate and increased residence time for water as well as influential materials thereby resulting in a limited scope of self-purification [2, 3] When the dependency on storage reservoirs impedes the availability of other freshwater resources, it is inevitable to monitor, maintain and enhance the water quality, especially in providing safe drinking water to the large population living away from these sources [4].

Lakes are characterized by distinct interactions between land, water and air through various physical, chemical and biological processes, thereby constituting interactive coupling among various components of the ecosystem. Whereas, the dam reservoirs exhibit confluential nature of the rivers and lakes and their physical, chemical and biological characteristics are commonly affected by the seasonal fluctuations in the incoming water, and to a large extent, the reservoir characteristics. Another characteristic difference
exists between the lakes and reservoirs are in the residence time of the carrying water [5, 6]. Reservoirs are more frequently updated with the flowing river water giving rise to a lesser residence time than the lakes, giving rise to differences in expectations about the water quality. In addition, the other factors contributing to the quality aspects of these surface water storage bodies include basin lag, depth of impoundment, and frequency of water intake, provision of hydraulic structures for flow control, bank erosion control practices, sediment loading rates and sediment withdrawal mechanisms. Considering these features, it is important to compare and analyze the strategies in practice for maintaining water quality in lakes and reservoirs [7].

1.1. Water Quality in Lakes and Reservoirs

It is essential that water quality should be tested in terms of physical, chemical and biological parameters before it is being used for domestic, agricultural or industrial purposes. Being an open water body exposed to the environment, the water in the lakes and reservoirs are certainly prone for contamination, resulting in accumulation of several floating, suspended and dissolved solids along with a large variety of microorganisms [8-10]. Even though drinking water treatment plants generally anticipate such pollutants largely, and accommodate sufficient mechanisms to bring them down to the safe acceptable levels, the location of water intake points are invariably subjected to the risk of mixing with pollutants [11]. Another important aspect of continual degradation of water quality may be attributed to the age, depth coverage and composition of the sediments deposited on the banks and at the bed. A young lake is characterized by a low nutrient content, low plant productivity and clear water. With time, nutrients are brought in by the streams feeding the lake/reservoir, vegetal productivity increases and the waters become increasingly murky [12]. Considering all these factors, it is important to select the most significant parameters to minimally ascertain the existing water quality as well as to model the future trends.

Though there are many study reports available about the long term monitoring of water quality data for various hydrological gauge locations, there are not many studies in comparing the performance of lakes and reservoirs in view of the strategies for water quality maintenance. The main objective of the present study is to critically evaluate the differences in practices for maintaining water quality between an existing lake and a reservoir, for two different geo-climatic regions. The study also aims to identify the key factors influencing the seasonal and spatial (especially vertical) variations in the water quality in these water storage bodies. The present study constitutes a systematic comparison of the scopes, methodology and results available for a lake and a reservoir based on the available data.

2. Materials and Methods

2.1. Study Area

The present study compares the records of water quality monitoring collected from (1) Keban Dam Reservoir located in Turkey and from (2) Fateh Sagar Lake located in Udaipur, India (Figure 1). The Keban Dam is constructed on the Euphrates located in Elazig province of Turkey (38°48′25″N, 38°45′25″E) at the confluence of rivers Munzur, Peri, Murat and Karasu, having a total storage capacity of about 30.6 billion cubic meters with a maximum water depth of 163 m at its full supply level. This particular region of Turkey is characterized by a semi-arid climate with cyclic hot summers and extended rainy winters. Being one of the largest reservoirs in Turkey, it has a huge drainage area of about 64100 square kilometres, making the reservoir susceptible to severe environmental contamination especially from agricultural runoff. The study therefore focused on collecting the seasonal and vertical variations in some of the most important water quality parameters such as temperature, dissolved oxygen, cations and anions [13].
The city of Udaipur in India is known as the “Venice of the East” and the “City of lakes” as being a home to a large number of inland water bodies including freshwater lakes. The historic Fateh Sagar Lake is operational for more than 350 years, and is proved to be crucial for maintaining domestic, agricultural and ecological water needs of the city. The city of Udaipur is characterized by the typical arid climate with prolonged hot summers and freezing winters. The Fateh Sagar Lake (24°55′ N, 73°42′ E) covers an area of 4.0 square kilometers with a maximum depth of 13.4m. Since the average annual rainfall is only 62.5 cm from the catchment area of 53.66 square kilometers, the lake is maintained by confronting groundwater contributions. As evidenced by the symptoms of urbanization and green revolution, the lake water quality began to deteriorate by the unaccountable sewage outlets joining the lake. Hence a detailed study was conducted to collect the water quality parameters pertaining to the physico-chemical and biological contamination of the lake water [2].

![Figure 1](image-url)

**Figure 1.** The geographic location of (a) Fateh Sagar Lake, India and (b) Keban Dam Reservoir, Turkey

3. Comparison of Case Studies
The water quality analyses in these two surface water sources were provided with distinctive analytical methods particularly specific for the intended parameters of the study. Considering the significance of anthropogenic contamination of the lake, the water samples from the Fateh Sagar Lake were primarily analyzed for the physico-chemical and bacteriological parameters. The samples were also analyzed for the seasonal variations in the selected parameters for a period of 2 complete years. However, the typical hydrologic characteristics of the catchment area of the Keban Dam Reservoir suggested detailed analysis of the physical and chemical parameters, both seasonally and vertically in the water column of the reservoir (up to a depth of 30m). Details of the studied parameters are given in Table 1.
Table 1. Summary of the data obtained from the two water resources under consideration

| Parameters                           | Fateh Sagar Lake                | Keban Dam Reservoir              |
|--------------------------------------|---------------------------------|----------------------------------|
| Temperature (°C)                     | 28.5+-5.7                       | 16.28 +-1.93                     |
| pH                                   | 8.2+-0.4                        | pH                               |
| Total alkalinity (mg/L)              | 177+-10                         | Electrical Conductivity (µS/cm)  |
| Total hardness (mg/L)                | 180+-10                         | Bicarbonate and carbonate (mg/L) |
| Dissolved oxygen (mg/L)              | 9.0+-1.4                        | Dissolved oxygen (mg/L)          |
| Biochemical oxygen demand (mg/L)     | 4.06+-0.88                      | Sodium and Potassium (mg/L)      |
| Chemical oxygen demand (mg/L)        | 26.9+-4.0                       | Calcium and magnesium (mg/L)     |
| Total bacterial count                | 49.3+-19.8 x 10³               | Ammonia, nitrite and nitrate (mg/L) |
| Total coliforms (MPN/100 ml)         | 1144+-908                       | Sulphate and phosphate (mg/L)    |
| Total coliforms by membrane filtration technique | 1075+-903                      | Chloride (mg/L)                  |

For the samples from Fateh Sagar Lake, the seasonal variations in average pH were found in the range of 7.80 to 8.70. The World health Organization (WHO) permissible limit for pH is 6.5−8.5. High values of pH during summer is observed to be due to low level of water and low concentration of nutrients whereas the low pH values in monsoon can be attributed to the dilution caused by the rainwater. Total alkalinity, which was found in the range of 165 to 193 mg/L, was within the permissible limit of 200 mg/L. The average value of total hardness was found in the range of 169 to 194 mg/L, indicating that lake water was suitable for drinking purposes. The average values of dissolved oxygen varied between 7.2 and 10.8 mg/L. The biochemical oxygen demand (BOD) was found in the range of 2.8 to 5.3 mg/L with the highest BOD values in winter 2012 and lowest value in summer 2012. The WHO has set a desirable tolerance limit for BOD which is 3 mg/L. The average values for chemical oxygen demand (COD) were between 21.9 and 32.0 mg/L. The values of COD were quite higher than the permissible limit of WHO (10 mg/L). Total bacterial count was observed high in monsoon season in terms of maximum probable number (MPN) indicating that the lake water was severely contaminated by bacteria and such water can be used...
only after proper disinfection. The relative significance of the selected parameters was evaluated using correlation analysis. The results indicate that temperature has positive correlation with pH and total hardness and DO also has positive correlation with BOD and COD, whereas the correlation between ionic and organic parameters was found to be negative. From the study it has been inferred that authors have monitored only a few physico-chemical and bacteriological parameters. Therefore there is a need to monitor all the parameters to explain the water quality of the lake in better ways.

Considering the scenario of the Keban Dam Reservoir, the temperature displayed a homogeneous trend until mid-spring and then thermal stratification occurred between 10 and 20 meters during summer. No significant differences were detected in electrical conductivity among the monitored depths. Unexpectedly pH did not show strong correlations with cations and anions. However most pH values were above 7, indicating that the reservoir is a relatively alkaline system. The vertical distribution of dissolved oxygen during the mixing and stagnation periods was relatively uniform, while the concentrations in the water column gradually decreased from mid-spring to late autumn. The significance of the parameters was evaluated using correlation analysis. The strongest correlation of electrical conductivity was detected with sulfate ($r^2=0.65$), the second major anion in the reservoir. Vertical changes of magnesium, chloride and sulfate were not statistically significant. Although sodium and potassium showed increasing tendencies in hypolimnion, the bicarbonate, being the dominant anion, showed an increasing trend in hypolimnion. Magnesium, sodium, potassium, sulfate and chloride are relatively conservative both in their chemical reactivity and small biotic requirements under typical freshwater conditions while calcium and carbonate are more reactive and exhibit marked seasonal dynamics. A general trend with $\text{Ca}^{2+}>\text{Mg}^{2+}>\text{Na}^+>\text{K}^+$ and $\text{HCO}_3^->\text{SO}_4^{2->}\text{CO}_3^{2->}\text{Cl}^-$ was determined in Keban Dam Reservoir.

3.1. Significance of Thermal Stratification

Dissolved oxygen was lower than acceptable levels in the euphotic layer of the Keban Dam Reservoir and reached very low levels in the hypolimnion, indicating thermal stratification. Oxygen depletion then progresses upwards. Low oxygen saturation values were observed below the epilimnion which is a typical characteristic of mesotrophic/eutrophic lakes. However, there were no such observations available for the Fateh Sagar Lake. Though the lake has sufficient surface coverage, the variations in temperature may not show sufficient differences due to the limited depth (13.4 m) as well as the typical tropical climate prevailing in the region. Similarly, the lake water gets natural neutralization depending on the parent lake bed material, which is further balanced by the carbonate-bicarbonate buffering action. This observation is justified by others in similar conditions as well [14].

3.2. Eutrophication and Water Quality

The physico-chemical and biological characteristics of water in lakes and reservoirs are mostly influenced from seasonal variations in runoff, water level fluctuations, and the hydraulic residence time [18]. The dissolved-oxygen concentration can decrease in response to decomposition of dead algae that settle below and in response to the biological and chemical oxygen demand of the sediments. The oxygen demand from these processes may completely deplete the oxygen in the water near the lake bottom, creating a condition of anoxia. Dissolved oxygen, pH, and chlorophyll-a levels in the Keban Dam Reservoir peaked in the wet season; pH, chlorophyll-a, and total phosphorus in several cases were recorded above the recommended guidelines. In case of Fateh Sagar Lake, the domestic sewage pollution has made the highest impact on the water quality as evident from the bacteriological results such that presence of
inorganic nutrients to supplement algal growth were greatly suppressed by the active decomposition of fecal organic matter reaching the lake water. The results indicate clear evidence of E. coli strains and postulate remarkable estimates that these microorganisms could develop sufficient antibiotic resistance.

3.3. Microbial Ecology in Reservoirs

Reservoirs built for hydroelectric purposes can induce significant ecological transformation on aquatic systems that change the water quality at spatial and temporal scales. The amount and quality of in-flowing water into a reservoir affects nutrient loading rates, which can influence water quality. Seasonal rainfall variation influences inflow volume in quantity and quality. These changes typically reflect the watershed geology, land use, landscape patchiness, and climate. Spatial gradients are formed along the longitudinal axis of reservoirs and reflect 3 reservoir compartments. Fluvial zone is characterized by comparatively high water velocity, nutrient availability, and lower light penetration. Similarly Lacustrine zone is characterized by still water, higher light penetration, and lower nutrient availability for uptake by phytoplankton due to sedimentation processes that occur in the upstream zone of the reservoir. Concentrations of Chl-a ranged from 2.1 to 53.4 μg/L, with higher mean values (P < 0.01) during the wet season (20.59 μg/L) compared with the dry season (6.48 μg/L).

4. Proposed Strategies for Water Quality Improvement in Lakes and Reservoirs

There is plenty of evidence of the deteriorating water quality in active surface water resources, especially in lakes and reservoirs. In order to improve the quality of bulk water from surface water bodies, it is important to use economical, most accurate and reliable techniques to monitor the water quality parameters. Electrochemical sensing technique is one of the emerging techniques to fall under the category [15]. Advanced monitoring systems are also developed using spectrophotometer as optical decision making system (ODMS) to monitor the lake water quality parameters effectively [16]. Very quickly internet of things (IoT) enabled technologies will be widely preferred for the water quality monitoring [17]. The long-term monitoring of various environmental features is being carried out by various reputed agencies from time to time. Unfortunately, most of the results are not influential in making long-term strategies for protecting the water bodies as well as to bring back the water quality using sustainable means. Hence it is essential to review some of the characteristic features of these water bodies to identify the causes of failure and actions to be taken to rectify them. A summary of the existing practices and a proposed plan for improving water quality in lakes and reservoirs are presented here (Table 2).

**Table 2.** Comparison of various water quality indicators and expected changes in action plan

| Indicators          | Impacts                                      | Current practice                      | Proposed action plan                          |
|---------------------|----------------------------------------------|---------------------------------------|------------------------------------------------|
| Sediment loading rate | low, negative, reduction in storage volume     | high, negative, reduction in storage volume | derive accurate dynamic loading rate, fixed profiling system can be attached to any fixed structure mapped with catchment hydrology |
| Deposited sediments  | low, negative, causes turbidity, anaerobic zone | high, negative, creates anaerobic zone, faster changes in effective storage volume, high percentage of clay and silt particles | empirical estimation, irregular dredging frequency |


Water temperature

- low, shallow depth, susceptible to local weather
- higher, visible vertical thermal stratification, depends on larger climate, higher evaporation

Dissolved Oxygen

- high, better solubility at lower temperature, limited variability over surface, not clear to see the DO sag curve
- high, reduced solubility at higher temperatures, more susceptible for variations at depth, more horizontal variability with inflow, visible DO sag curve

External nutrient loading

- Variable but relatively predictable, moderated by biogeochemical influences
- higher loading, greater water level fluctuations, often unpredictable

Nutrient dynamics

- significant vertical gradient, algal blooms, low internal loading
- irregular, high impact over horizontal gradients, complex interaction with sediment cycle

Dissolved organic matter

- relatively constant, refractory fraction predominates, Littoral/wetland sources predominate
- Benthic sources predominate, irregular, often high, refractory fraction predominates

Phytoplankton and other life forms

- limited impact, predominant limited inorganic nutrients, vertical and seasonal gradient predominate, small horizontal gradients
- constant productivity horizontally, marked horizontal gradients, predominant limited inorganic nutrients

5. Conclusions

- negligible in evaluating aquatic biochemical activity, no control on evaporation
- infrequent analysis, limited measurements for the entire source, limited scope for developing re-oxidation zone
- pollution prevention based on self purifying capacity, higher dependency on stagnant dilution
- limited understanding of algal-bacterial symbiosis kinetics, by-products of complex reactions are unaccounted, conservative approach bulk parameter, source-independent approach, limited fractionation
- case-specific analysis, limited bio-accumulation database, highly variable productivity

- improved biochemical kinetic to predict the water quality parameters, possible to reduce evaporation by innovative physical and agronomic methods
- Buoy-based profiling systems for high-energy environments, sensor-based continuous real-time monitoring systems, natural mixing to elaborate re-oxygenation rate
- hot-spot identification and stringent policy to limit waste mixing to the water bodies, dilution by mixing for increased assimilation integrated mass balance approach to account of possible species interactions, coupled flow-transport modeling
- Pontoon-Mounted profiling system with meteorological package, activity-based classification, source-based characterization, accountability of temporal variation sensor-based continuous real-time monitoring system, synchronized biomarkers to limit level of nutrients accumulations
Regular monitoring of water quality of lakes and reservoirs and its assessment is essential to decide usefulness for a specific beneficial use. The present manuscript highlights the importance of water quality monitoring with more emphasis on microorganisms found in waters of lakes and reservoirs and their significance in water quality. It was inferred that there exist a lot of variations in water quality parameters, both variations in water quality parameters both seasonally as well as depth wise. The microbial ecology of reservoirs has been highlighted and indicates the presence of numerous microorganisms and their role in the reservoir. This information presents the importance of monitoring of water quality parameters and their seasonal and vertical variations in water quality with more emphasis to be given to biological parameters evaluation especially when the reservoir water is used for drinking purposes.

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