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Spatiotemporal Assessment of Water Quality and Quantity of the Kaptai Lake at Rangamati, Bangladesh - An Approach of Remote Sensing, Field Investigation and Laboratory Analysis

Mahmud Al Noor Tushar, Arman Hossain, Mukter Hossen, Md. Ezaz Ahmed and Md. Bodruddoza Mia*

Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh

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ABSTRACT: Monitoring water quality and quantity is essential for sustainable water resource management. This study investigates changes in the extent and water quality of Kaptai Lake using remote sensing, field measurements, and laboratory analysis. Analysis of Landsat TM/OLI images from 1989, 2000, 2010, and 2021 shows that the lake's water extent ranges from 380 km² (in 2010) to 435 km² (in 2021), with an average of 407.5 km². The extent of water decreased by approximately 3% from 1989 to 2010 and increased by about 5% from 2010 to 2021 due to changing rainfall patterns, dam operations, sedimentation, and land use changes. Seasonal variations in chlorophyll-a concentration and turbidity, analyzed using Sentinel 2B images from 2022 and 2023, indicate mesotrophic to eutrophic conditions and higher turbidity in post-monsoon. The study found that nutrient enrichment from untreated sewage, agricultural runoff, and algal growth affect chlorophyll-a levels, while development activities, excessive rainfall, and sedimentation influence turbidity. Linear regression analyses show strong positive correlation between field obtained and image derived values both for chlorophyll-a (R^2 0.621) and turbidity (R^2 0.698). Physico-chemical parameters such as pH, EC and temperature have been measured in the field and hydrochemical parameters including, cations and anions have been measured by laboratory analysis to assess the contemporary water quality status. The average values for pH, EC and temperature are 7.55, 119.85 μS/cm and 22.17 °C respectively. The cationic dominance in the studied segment of the Lake is in the order of Ca^{2+} > Na^{2+} > Mg^{2+}>K^{+} > Fe^{2+} >Mn^{2+}. On the other hand, the anions are in the order of $HCO3^{-}$ > $SO4^{2-}$ > Cl^{-} > NO^{3-}. All the physico-chemical parameters of the lake water fall within the Bangladesh Drinking Water Limit (BDWL) and are not linked to chlorophyll-a and turbidity variations. The findings of this study can help mitigate the deterioration of Kaptai Lake by addressing water quality and extent issues, promoting effective and sustainable lake management strategies.

Keywords: Kaptai Lake; Satellite Image; Water Quality; Water Extent; Seasonal Variation; Sustainable Management

INTRODUCTION

Wetlands are one of the crucial parameters in the hydrologic cycle (Razzak et al., 2012). In general, wetlands serve as reservoirs that receive and discharge water through diverse mechanisms such as precipitation, infiltration, percolation, surface run-off and evapotranspiration by plants. Bangladesh is blessed with abundant water resources that are dispersed throughout the country (Rahman et al., 2014).

*Corresponding author: Md. Bodruddoza Mia

Email: bodruddoza@du.ac.bd

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Kaptai Lake is the largest man-made lake in Bangladesh, located in the Rangamati Hill District of southeastern Bangladesh. The lake was created in 1962 as a result of the construction of the Kaptai Dam on the Karnaphuli River (Bashar et al., 2015). The main purpose of the dam was to generate hydroelectric power for the region. The Kaptai Lake is surrounded by lush green hills and offers scenic beauty to visitors. The lake also supports a variety of fish species, making it a popular destination for fishing enthusiasts. Currently, Kaptai Reservoir supports small-scale fisheries, which contribute over 63,000 tonnes of freshwater fish annually and have a wide variety of fish species (Ahmed et al., 1999). Aquatic Research Group (Halder et al., 1991) recorded 49 indigenous fish species and 5 exotic fishes in this lake. The indigenous tribal communities, such as the Chakma people, live around the lake and rely on its resources for their livelihoods. Overall, Kaptai Lake is a significant landmark in Bangladesh, offering a blend of natural beauty, aquatic diversity, cultural diversity, and recreational opportunities for visitors to enjoy (Islam et al., 2021).

Water quality refers to the essential elements in water required for optimal growth of aquatic organisms (Ahatun et al., 2020). The factors that contribute to favorable growth in water bodies include dissolved oxygen (DO), hardness, turbidity, alkalinity, nutrients, and temperature, among others, which are commonly found in most water bodies. Human activities and the absence of environmental regulation contribute to an increase in these concentration levels. Evaluating the quality of water resources in any region is crucial for developmental activities, as rivers, lakes, and manmade reservoirs serve as sources of water supply for domestic, industrial, agricultural, and fish farming purposes (Pal et al., 2015). Nutrients are essential elements for maintaining a productive and balanced aquatic environment (Ahatun et al., 2020). For their life, growth, and reproduction, all aquatic species, including fish, are utterly dependent on nutrients. The availability of certain nutrients is linked to the presence of chlorophyll in the water, indicating the abundance of phytoplankton (Shukla et al., 2013). Therefore, nutrient availability directly influences the productivity of the water body (Rahaman et al., 2013). Insufficient nutrients lead to unproductive water bodies, while excessive nutrients cause eutrophication through algal bloom, making the water toxic. By giving all aquatic creatures in water bodies initial nutrients and energy, algae play a crucial role in aquatic ecosystems. Algal bloom, or abnormal and excessive algal development, however, can have negative repercussions (Stauffer et al., 2019). Therefore, it is essential to maintain nutrient concentrations within acceptable limits to promote a healthy aquatic environment and ensure the optimal production of aquatic organisms, including fish (Senthilkumar et al., 2008). Being one of the most significant water bodies in Bangladesh both from the ecological and economical point of view it's urgent to monitor the spatiotemporal water quality and quantity of the lake for the sake of sustainable water resource management.

The use of satellite imagery for monitoring lake water quality has been gaining popularity over the years as technology has advanced. The integration of satellite data for monitoring water quality has been happening gradually since the late 1990s and early 2000s. The availability of high-resolution satellite imagery, along with advancements in remote sensing techniques and data processing capabilities, has made it more feasible to monitor water bodies on a global scale. However, it took time for the technology to become widely accessible and for the necessary infrastructure to be developed. (Carpenter et al., 2011). Multiple research and surveys have been conducted on the lake water quality in Bangladesh but the number is only a few in and around the study area. These studies were mainly focused on assessing the water quality of the lakes and to identify the possible sources of pollution (Karmakar et. al., 2011; Rahman et.al. 2014; Bashar et al., 2015; Barua et.al. 2016; Rubel et.al. 2019; Hoque et. al., 2021; Islam et. al., 2021).

All the aforementioned studies were focused on assessing the seasonal variation of quality parameters based on direct measurements covering only a limited portion of the Lake. On the other hand this very study has assessed the spatiotemporal variation of water quality and quantity of the entire lake area through time series data analysis under a remote sensing environment that is entirely a new approach of study for this region.

The key objectives of the current study was to assess the spatiotemporal variation in the quality and quantity of Kaptai lake using satellite imagery and to validate the image derived results through field investigation. The first objective focuses on understanding how the water quality and water volume (or extent) of Kaptai Lake change over time and across different locations. Using satellite imagery allows researchers to analyze these variations on a large scale over multiple time periods. The satellite data can provide crucial information on key water quality indicators such as turbidity, chlorophyll content, or suspended sediment concentration, as well as changes in the surface area of the lake. By observing these changes, the study can identify any trends in water quality degradation or reduction in lake volume due to natural or human-induced factors such as sediment deposition, pollution, or deforestation. Satellite imagery analysis, while powerful, often requires validation to ensure the accuracy of its findings. In the second objective, field investigations would be conducted to ground-truth or validate the results obtained from satellite images. This might involve collecting water samples from different locations in Kaptai Lake and analyzing them for various parameters. The field data is then compared with the satellite-derived measurements to confirm the reliability of the satellite imagery analysis. If discrepancies are found, they can be adjusted, ensuring a more accurate assessment of the lake's condition. The objectives of the study have remarkable relevance with the 8th Five Year Plan (FYP) of Bangladesh in the national context and the SDG coals 6.6 and 14 in the international context. Additionally, the study will help the decision makers in taking better actions to sustainably reduce water pollution and to protect and restore the lake ecosystem.

STUDY AREA

The study area extends between the latitudes of 22°**30**'N to 23°00'N and the longitudes of 92°00'E to 92°20'E and encompass the overall extent of the Kaptai Lake, Rangamati **(**Fig 1**)**. Geographically it belongs to the Rangamati district and bounded by Nannerchar and Longadu Upazilla to the North, to the east by Barkal, Juraichari Upazilla and Mizoram state of India and to the west by Rangamati sadar Upazilla. The lake is tectonically belongs to the Eastern fold belt of Bangladesh and housed in consecutive ridges and valleys of Sitapahar, Rangamati and Barkal anticlines and possess irregular basin. The lake covers an area of 583 km^2 with a surface elevation of about 31.1m and holds volume 524,700 m³ of water (Suman et al., 2021). The lake discharges 1,707,000 m³ of water annually with a storage ration of about 0.31m (Banglapedia 2016).

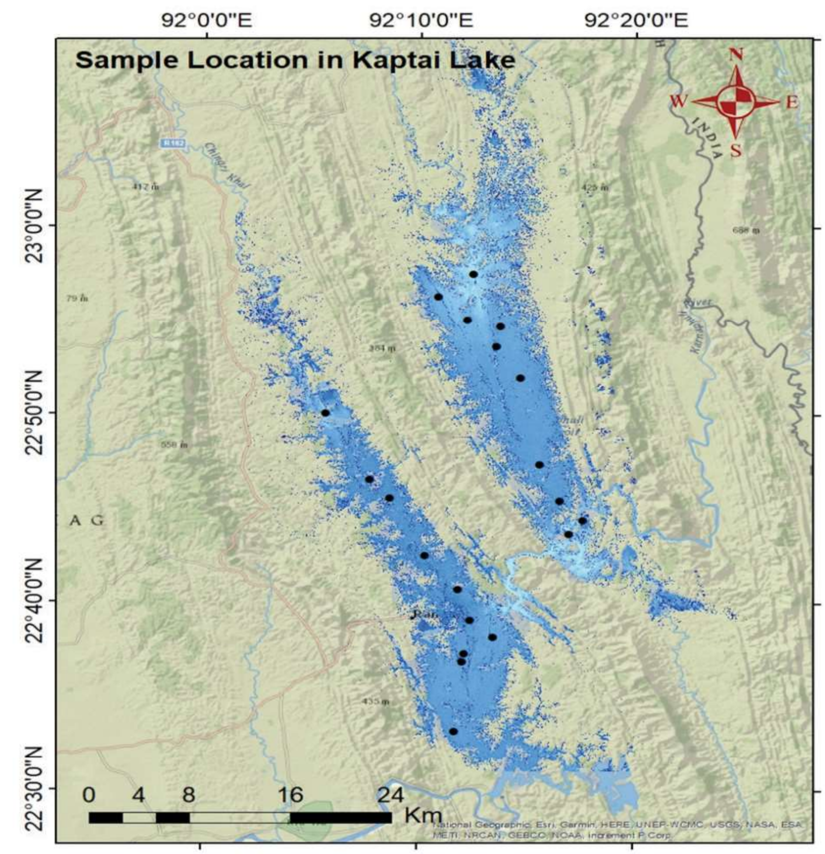

Figure 1: Map of the Study Area Showing the Sampling Locations

MATERIALS AND METHODS

The study is a compilation of satellite image processing, field investigation and laboratory analysis **(**Fig. 2**)**. Multiple satellite images, geospatial software, and in situ data collection instruments were used to conduct this research. The simplified methodological flow chart of the study are presented in figure 2. Water quality parameters such as pH, EC, TDS and temperature have been measured in the field and major cations and anions have been measured in the laboratory.

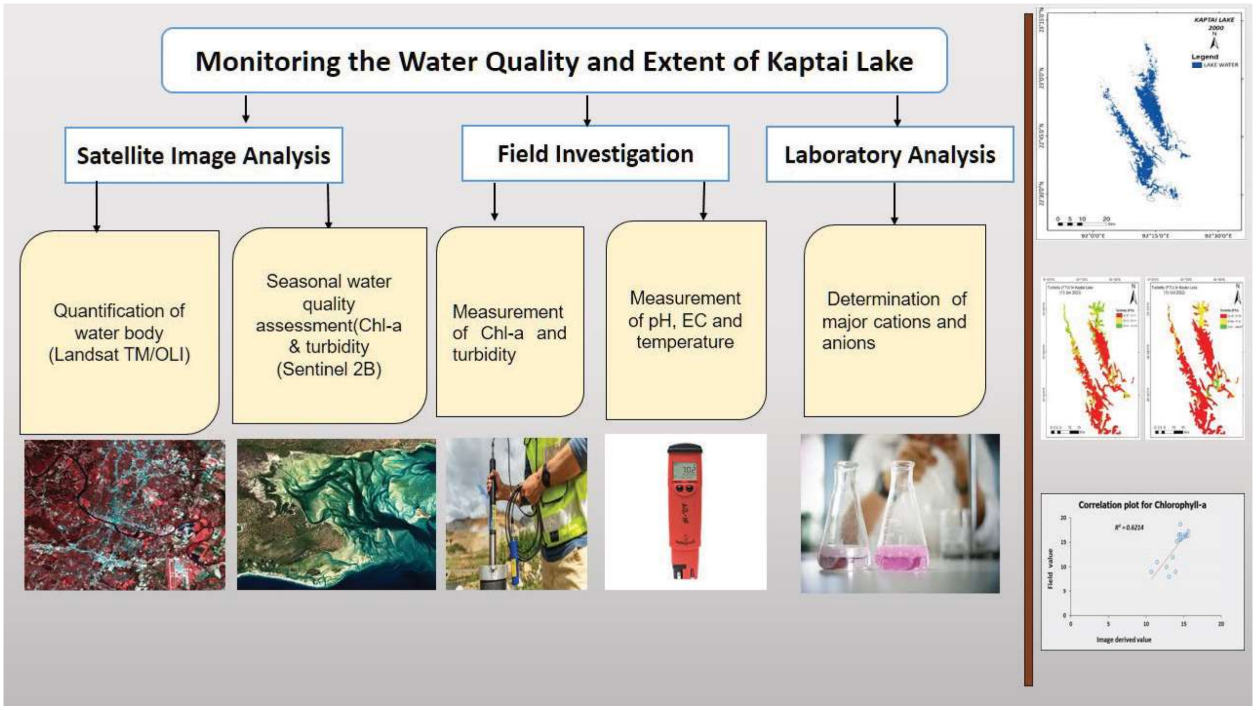

Figure 2: Methodological Flow Diagram of the Study

Satellite Image Analysis

Collection of Satellite Images

Landsat TM/OLI sensor images were employed to quantitatively monitor Kaptai Lake. The resolution of Landsat images was 30 meters. The lake's seasonal water quality parameters were assessed using Sentinel 2B sensor images, with the used bands of 20m resolution. The date of acquisition of the satellite images along with the sensor and resolution have been shown in the table 1.

Table 1: Satellite Images with Their Acquisition Date and Spatial Resolution

Sensor	Date of acquisition	Resolution (m)
Landset 5 level2 TM	13 January 1989	30
Landset 5 level2 TM	12 January 2000	30
Landset 5 level1 TM	23 January 2010	30
Landset 8 level2 OLI	05 January 2021	30
Sentinel2B	13 January 2023 (Winter)	20
Sentinel2B	15 October 2022 (Post-Monsoon)	20

Quantification of Lake Water Extent

The quantitative analysis of the extent of Kaptai Lake from 1989 to 2021 was conducted using four sets of Landsat TM/OLI images (Table 1), employing the Modified Normalized Difference Vegetation Index (MNDVI) method. Prior to classification, the images underwent rectification through radiometric and geometric techniques. Equation for MNDWI is-

MNDWI = (Green - MIR)/ (Green + MIR)…….(1)

Here, Green = Band 2, 3 and

MIR = Band 5, 6, 7

Assessment of Water Quality of the Lake

To examine the water quality parameters, namely chlorophyll-a concentration and turbidity, of Kaptai Lake during two different seasons (post-monsoon and winter), two high-resolution satellite images from Sentinel 2B (with a resolution of 20m) were carefully analyzed (Table 1). The process involved atmospheric correction of the images, followed by the calculation of reflectance values for the specific bands used in the Sentinel 2B images. This was achieved by employing the appropriate reference equation and metadata associated with the images.

The chlorophyll a concentration was determined utilizing Sentinel 2B satellite images by using the following formula:

Cchl-a = 113.23 x (R4/R5)2 - 311.67 x (R4/R5) + 216.76 …… (2)

In this context, "Cchl-a" denotes the obtained chlorophyll-a concentration (μg/L), while "R4" and "R5" refer to the reflectance values of the red (665 nm) and VNIR (705 nm) bands from the Sentinel 2B data, respectively (Wang et al., 2021).

As per Boyed (2015), the trophic status of Kaptai Lake was determined based on the average chlorophyll-a concentration values.

Turbidity is one of the vital quality parameter of water bodies and performs as a substitute for water clarity. The following equation, developed by Quang et al. in 2017 using sentinel 2B satellite image data and a linear regression model, was used to retrieve the spatial distribution of water quality in the Kaptai Lake.

Turbidity (FTU) = 380.32 x R4 – 1.7826…… (3)

Field Investigation

In-situ Observation of Water Quality

To validate the image-retrieved data on chlorophyll-a and turbidity in Kaptai Lake, the Aqua TROLL 600 Multi parameter Sonde was utilized as an in-situ device to measure these parameters. To take the measurements at first the sensors were calibrated as per the manufacturer's guidelines. Then the sonde was deployed in the water at the desired sampling location, ensuring that it is submerged at the correct depth for accurate readings. The sensors were then allowed to stabilize and then the data collection was started. The real-time measurements were retrieved via the connected device and the data was stored in excel spreadsheet format. The sensors were cleaned after the data collection to avoid cross-contamination for future measurements (Fig 3).

Figure 3: In Situ Field Data Collection Using Aqua Troll Multi Parameter Sonde

In situ measurements have been taken from some selective locations of Kaptai Lake. The locations of the in situ data collection points are shown in the study area map (Fig. 1).The ground truth validation for image derived parameters (Chlorophyll-a and turbidity) has been performed through linear regression analyses between image derived and field obtained values. The analyses have been performed in IBM SPSS Statistics 20.

In-situ Observation of Physico-chemical Parameters

The physico-chemical parameters such as EC, pH, and temperature have been measured in the field to study the contemporary water quality status. pH is the concentration of hydrogen ions and it has been measured in the field by **HANNA HI98121** pH meter. EC means Electrical Conductivity which indicates the potential of a water sample to do electrical activity. Both the EC and temperature have been measured by **HANNA HI98311** EC meter (Fig. 4).

Laboratory Analysis

The hydrochemical parameters such as major cations and anions have been assessed in this section from the Kaptai Lake water. This step has been divided into three sub-steps for better understanding of the process in the following way

Water Sampling

Water samples were collected from 13 locations of the Lake (Fig. 1). The samples were collected on January 15, 2023. Three types of samples were collected in the study such as unfiltered and un-acidified samples in 125 ml polyethylene bottle, filtered and un-acidified samples in 60 ml polyethylene bottle and filtered and acidified samples in 60 ml polyethylene bottle. At first each sample bottles were rinsed in a proper manner with water to clean anything remaining inside the bottles. For filtration a 0.45 µm syringe-head membrane filters has been used to remove colloidal and unwanted particles. One of the two 60 ml filtered samples were acidified using 1% concentrated HNO3 to lower pH of the water less than 3 to avoid precipitation of dissolved constituents. Then the samples were levelled properly labelled with Sample ID, Date and whether they are filtered or non-filtered, acidified or non-acidified.

Hydrochemical Analysis

The laboratory analyses for the major cations and anions from the collected samples have been performed in the Geochemistry laboratory of department of Geology, University of Dhaka. Major cations such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Fe^{2+} and Mn^{2+} have been analyzed through Atomic **Absorption Spectroscopy (AAS)** (Savant AA GBC). On the other hand major anions such as, Cl^{-}, SO_4^{2-} and NO_3^{-} have been analyzed through **Ion Chromatography System (ICS)** (DIONEX ICS-1100). Only the concentration of HCO_3^{-} was measured by the titration process (Fig. 5).

Analytical Accuracy Check

The accuracy of the laboratory analyses have been checked through ionic balance. Ionic balance refers to the equilibrium between positively charged ions (cations) and negatively charged ions (anions) in a solution, typically water (Morgan, 1995; Appelo and Postma, 2004). The following equation has been used to check the balance:

Balance (%) = (Σ Cations- Σ Anions) / (Σ Cations + Σ Anions)*100

If the value is within ±5%, the sample is considered highly accurate. A balance within ±10% is generally acceptable, but if it exceeds ±10%, the accuracy is questionable (Hounslow, 1995)

RESULTS AND DISCUSSION

Water Extent

The results of Landsat TM/OLI image analysis showed that the total extent of the lake was 409.86 Sq. Km in 1989, 403.82 Sq. Km in 2000, and 396.10 Sq. Km in 2010 and 415 Sq. Km in 2021. **(**Fig 6**).**

Figure 4: pH and EC Meter Used for Taking Field Measurements

5(a) AAS (Savant AA GBC)

5(b) ICS (DIONEX ICS-1100)

5 (c) Titration Analysis

Figure 5: Laboratory Analysis of Major Cations and Anions (Source: Hossain 2023)

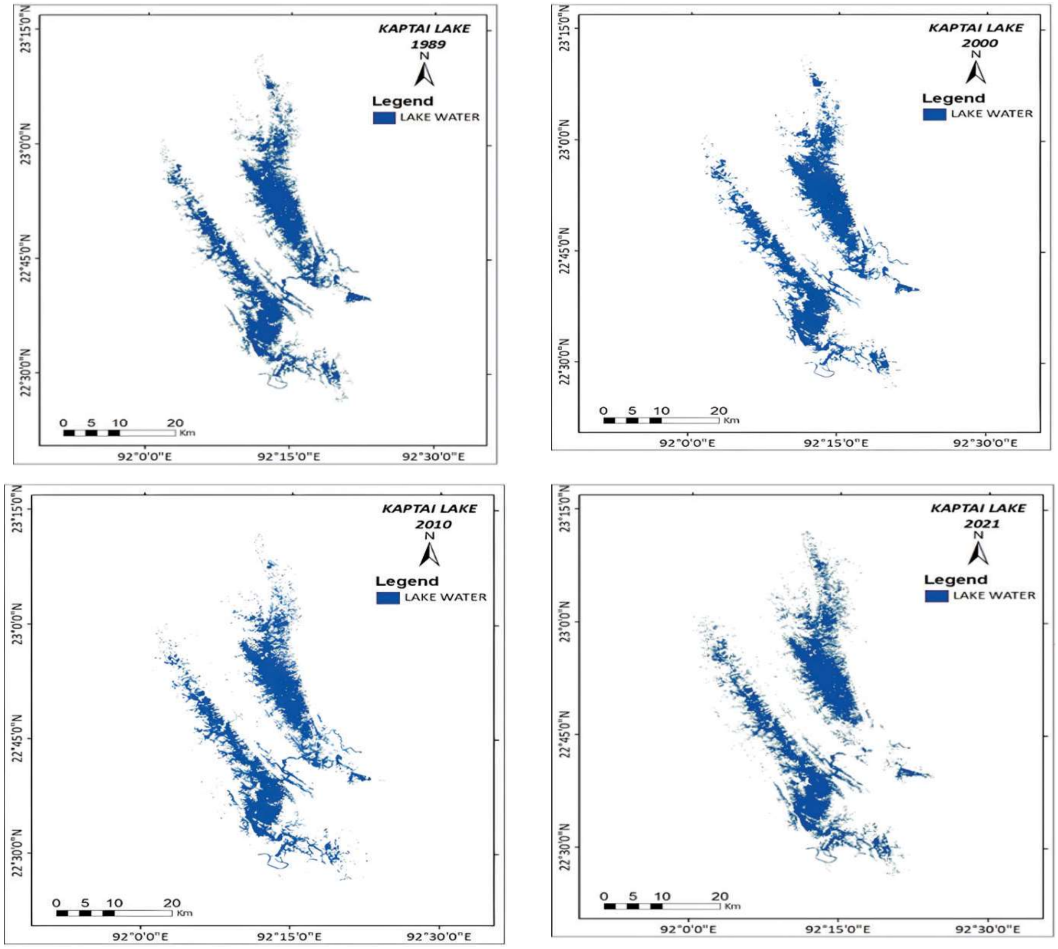

Figure 6: Spatiotemporal Variation of the Extent of Kaptai Lake

There is a subtle but gradual change of the area of the lake was found where it was decreased from 1989 to 2010 and from then it was increased upto 2021(Fig. 7). It is noticed that the change occurred mostly in the north-east, north-west and south-east region of the Kaptai Lake. Nevertheless, water body remains the same in the centre of both parts of the lake. That means the change occurred only in the peripheral region of the lake.

Water Quality

Geospatial arrangement of water quality factors like chlorophyll-a and turbidity were obtained through the utilization of Sentinel 2B sensor pictures capturing the conditions of Kaptai lake during two distinct periods. The seasonal images are selected only for post-monsoon and winter season (Fig. 8 & 9).

Chlorophyll-a

Minimum concentration of chlorophyll-a in both season was same (2.29 µg/L). Maximum concentration of chlorophyll-a in post-monsoon was 23.53 µg/L and in winter was 20.01 µg/L and therefore the values are decreased from post-monsoon to winter season. Spatially chlorophyll-a concentration varies from 13 to 18 µg/L, concentrated in the central regions of both lake sections (Fig. 8). This measurement pointed to the eutrophic condition of Kaptai Lake across the seasons, spanning from post-monsoon to winter. The lower value of chlorophyll-a concentration is located in the north-east and slightly south-east portion of the eastern part of Kaptai Lake (Fig. 8).

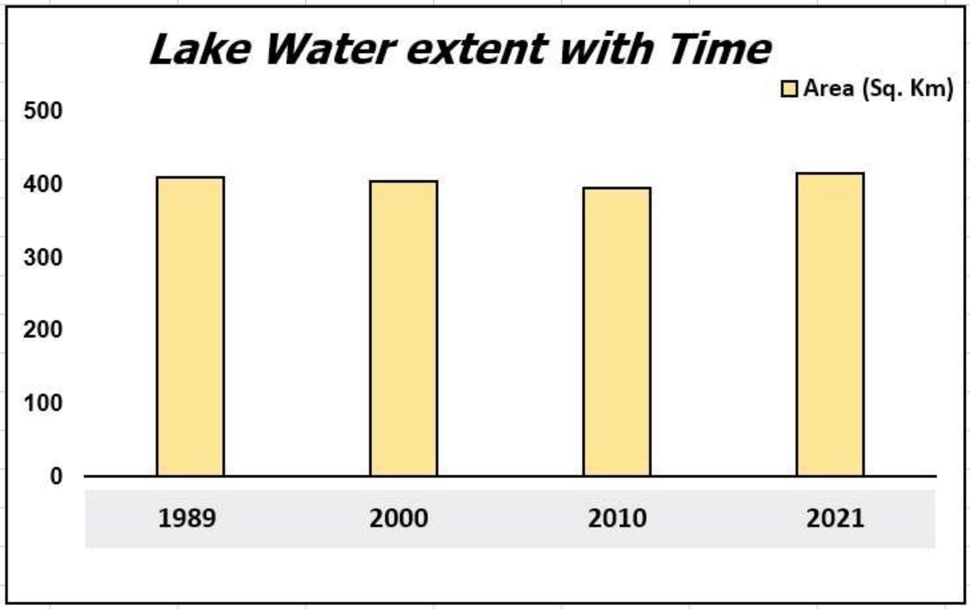

Figure 7: Extent of Kaptai Lake Water within the Time Frame from 1989 to 2021

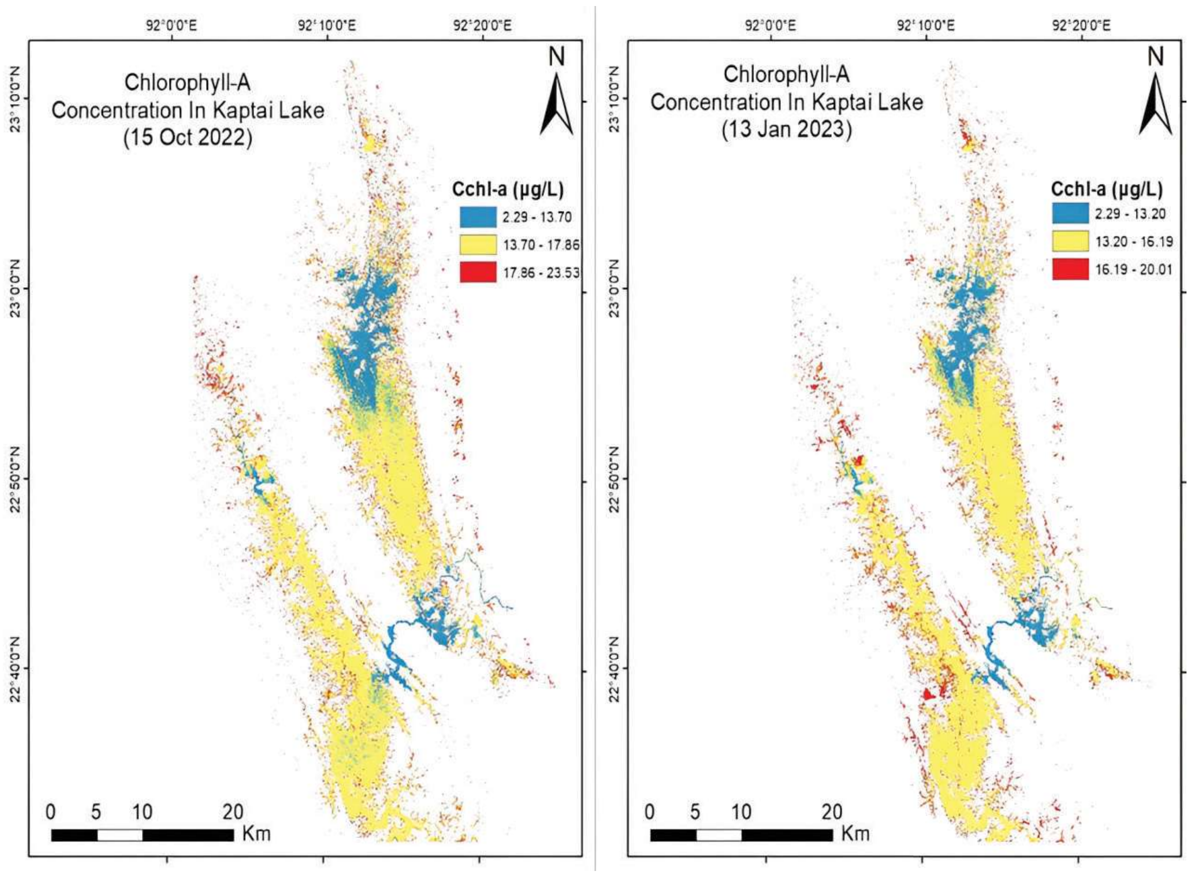

Figure 8: Spatial Distribution of Seasonal Chlorophyll-a Concentration within Kaptai Lake in 2022 and 2023

Turbidity

Minimum concentration of turbidity from the images increased from post-monsoon to winter period. In post-monsoon the value was 42.45 FTU and in winter the value was 43.82 FTU. Again the maximum value was 246.87 FTU in post-monsoon and 153.58 FTU in winter season. So the maximum turbidity value decreased from post monsoon to winter season. Spatial distribution of turbidity in Kaptai lake concentration showed mostly 42 to 58 FTU, which is located in the center of both parts of the lake. From the image it was noticed that the value increased from post-monsoon to winter season. The mid-range value of turbidity exist in the north-east part of the lake in winter season and very negligible in other areas. The high range value marked at the north-west position of the study area and also found in negligible area in the lake **(**Fig. 9**)**.

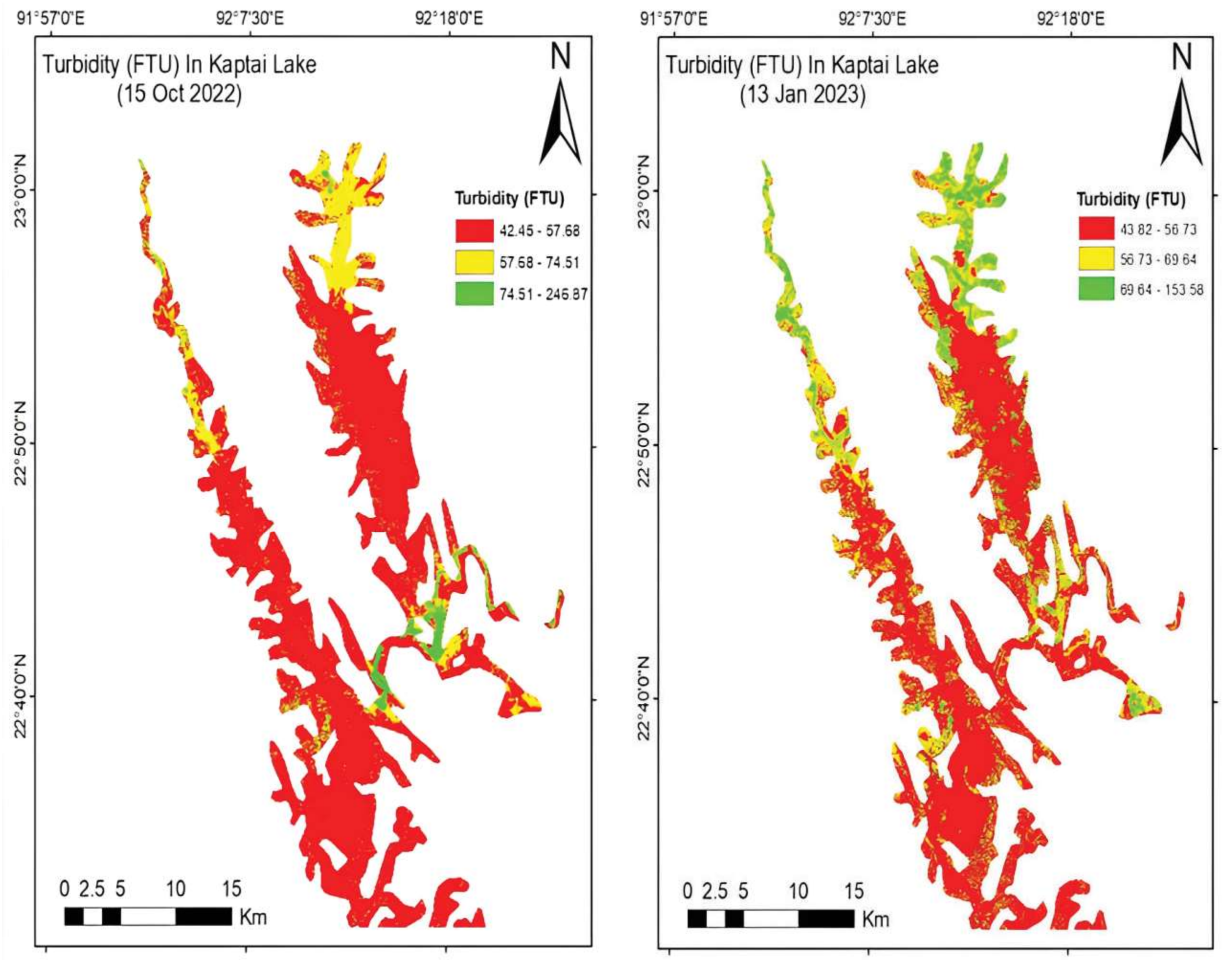

Figure 9: Spatial Distribution of Seasonal Turbidity (FTU) within the Kaptai Lake in 2022 and 2023

The periodic water quality parameters in Kaptai Lake can be represented by the summary metrics encompassing the lowest and highest values of the water characteristics during the two seasons **(**Table 2**).**

Table 2: Overview of the Periodic Water Condition in the Kaptai Lake

Image Based Water Quality parameters	Post-Monsoon		Winter	
	Min	Max	Min	Max
Cchl-a (μg/L)	2.29	23.53	2.29	20.01
Turbidity (FTU)	42.45	246.87	43.82	153.58

Chemical Properties of Water in Kaptai Lake

In-situ Physico-chemical Parameters of Water

Various physico-chemical parameters such as pH, electrical conductivity (EC) EC and Temperature have been measured by taking in-situ measurements at 13 locations within lake and the results are shown in table 3.

Table 3: In-situ physico-chemical parameters in Kaptai Lake

Sample no.	pH	EC (mS/cm)	Temperature (°C)
S1	6.9	132	21.6
S2	7.31	122	21.5
S3	7.56	123	21.7
S4	7.01	116	22
S5	7.69	116	21.6
S6	7.75	113	21.9
S7	7.8	115	21.8
S8	7.76	120	21.7
S9	7.72	118	21.5
S10	7.4	128	23.6
S11	7.72	121	22.9
S12	7.71	119	22.7
S13	7.77	115	23.7
Average	7.55	119.85	22.17

The value of pH ranges from 6.9 to 7.8 with an average value of 7.55. The value of EC varies from 113 µS/cm to 132 µS/cm with average value of 119.85 µS/cm. The lake surface temperature ranges from 21.5**°C** to 23.7**°C** with an average value of 22.17 **°C.** The pH varies from 6.9 to 7.8. The pH, EC, and temperature value do not vary significantly and may represent that the water body more or less is in a steady state condition and has not been affected from the water influx. A notable aspect is that the measurements were conducted during the winter season, which could serve as a contributing factor. The spatial distribution of pH, EC and Temperature within the selected portion of the Kaptai Lake are shown in figure 10.

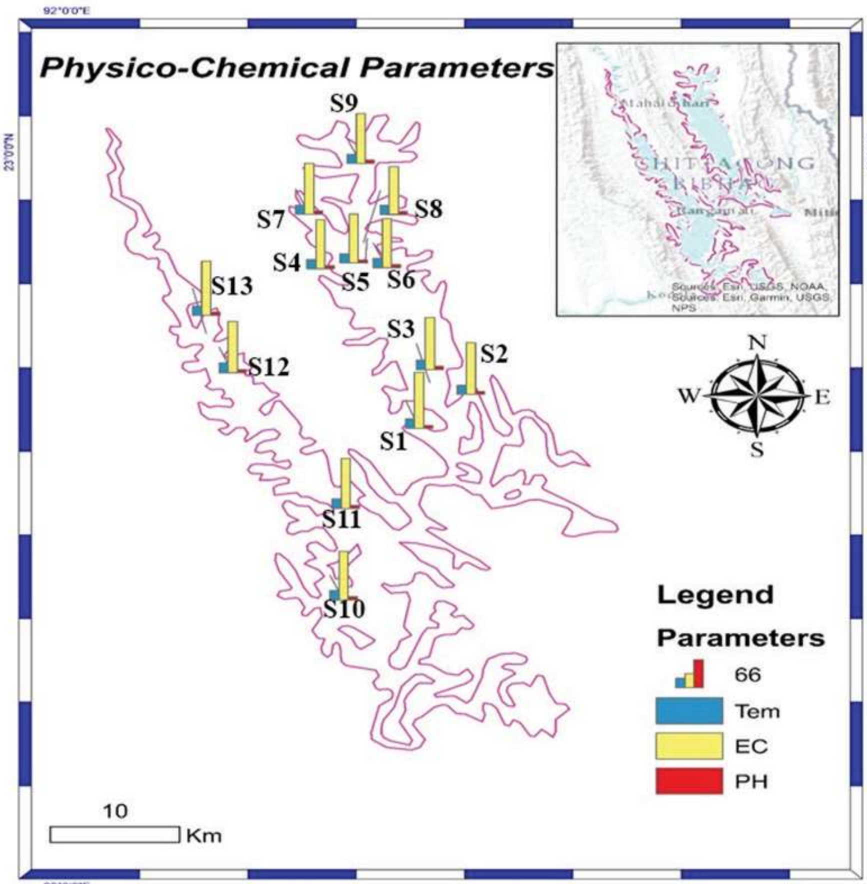

Figure 10: Spatial Distribution of In-situ Water Quality Parameters in Kaptai Lake where the Temperature is in °C and the EC is in µS/cm. The Measurements were Taken in January 2023

Figure 9 visualizes that all the parameters show a similar distribution pattern all through the study area. The value of temperature is the highest at the S13 and lowest at station 9. The value of pH is the highest at station 7 and lowest at the station 1. Station 1 and station 6 shows the highest and lowest value of EC respectively.

Laboratory Based Water Quality Parameters

Laboratory analyses have been performed to derive the major cations and anions of the water. The major cations include Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Fe^{2+} and Mn^{2+} and major anions include HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- etc. (Table 4)

The key statistical attributes of the cations and anions and their relationship with BDWL value are presented in table 5 and 6 respectively. The value of Ca^{2+} ranges from 23.99 to 43.25 mg/l with an average value of 33.96 mg/l where the average value is much lower than the Bangladesh drinking water standards for Ca^{2+} (75 mg/l). The value of Mg^{2+} ranges from 6.54 to 15.10 mg/l averaging at 12.35 mg/l and again within the range of Bangladesh drinking water Level (BDWL) of DPHE. The value of Na^{+} ranges from 9.34 to 49.36 mg/l with an average value of 28.16 mg/l and very much lower than the BDWL for Na^{+} (200 mg/l). The value of K^{+} ranges from 3.62 to 6.32 mg/l with an average value of 5.12 mg/l and falls within the BDWL that is 12 mg/l. The lowest and highest value for Fe^{2+} are 0.25 and 0.81 mg/l respectively with an average value of 0.50 mg/l and within the BDWL (0.3-1.0 mg/l). The value of total Mn^{2+} ranges from 0 to 0.04 mg/l averaging at 0.02 mg/l and much lower than the BDWL value that is 0.1 mg/l. From the above mentioned results it can be summarized that the cation contents of the Kaptai lake water is within the acceptable limit of Bangladesh Drinking Water Limit (BDWL) of DPHE that justifies the uncontaminated status of the sampled portion of the lake (Table 5).

Table 4: Results of Laboratory Analysis of Water Quality Parameters of Kaptai Lake

Sample ID	Cations						Anions			
	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	Fe2+ (mg/l)	$Mn2^{+}$ (mg/l)	HCO_3 -(mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	$NO3^-$ (mg/l)
S1	43.25	15.10	17.80	4.97	0.32	0.04	221.13	6.00	0.61	bdl
S2	41.23	13.65	17.71	4.73	0.40	0.02	213.50	5.90	12.96	bdl
S3	40.27	14.60	24.76	4.76	0.52	0.04	175.38	5.87	2.80	bdl
S4	33.18	13.71	17.68	4.90	0.65	0.01	183.00	6.10	10.54	bdl
S5	39.80	13.32	17.50	5.01	0.81	0.00	183.00	6.16	12.41	bdl
S6	33.17	13.73	46.19	6.26	0.66	0.01	183.00	19.14	45.34	bdl
S7	27.22	13.53	48.65	6.11	0.64	0.01	183.00	21.87	51.18	0.64
S8	35.44	14.23	48.50	6.32	0.51	0.02	167.75	20.91	52.02	bdl
S9	37.22	13.80	49.36	6.02	0.26	0.01	198.25	21.90	52.15	bdl
S10	36.51	14.26	47.40	6.17	0.25	0.03	205.88	26.21	52.01	2.29
S11	25.21	6.54	9.90	3.92	bdl	0.02	106.75	5.02	10.60	bdl
S12	23.99	7.43	11.34	3.79	bdl	0.01	122.00	6.21	13.10	bdl
S13	24.95	6.62	9.34	3.62	bdl	bdl	91.50	5.17	11.85	bdl

Table 5: Statistical Attributes of Major Cations and Anions of Kaptai Lake Water in Relation to BDWL

Major cations	Min value (mg/l)	Max value (mg/l)	Avg (mg/l)	BDL (mg/l)
Ca^{2+}	23.99	43.25	33.96	75
Mg^{2+}	6.54	15.10	12.35	30-35
Na^{+}	9.34	49.36	28.16	200
K^{+}	3.62	6.32	5.12	12
Fe^{2+}	0.25	0.81	0.50	0.3-1.0
Mn^{2+}	bdl	0.04	0.02	0.1
Major anions				
HCO_3^-	91.5	221.13	171.86	-
Cl^-	5.02	26.21	12.04	150-600
SO_4^{2}	0.61	52.15	25.19	400
NO_3^-	0	2.29	0.23	<1

The sample wise distribution of Cations can be given by the following bar diagram (Fig. 11)

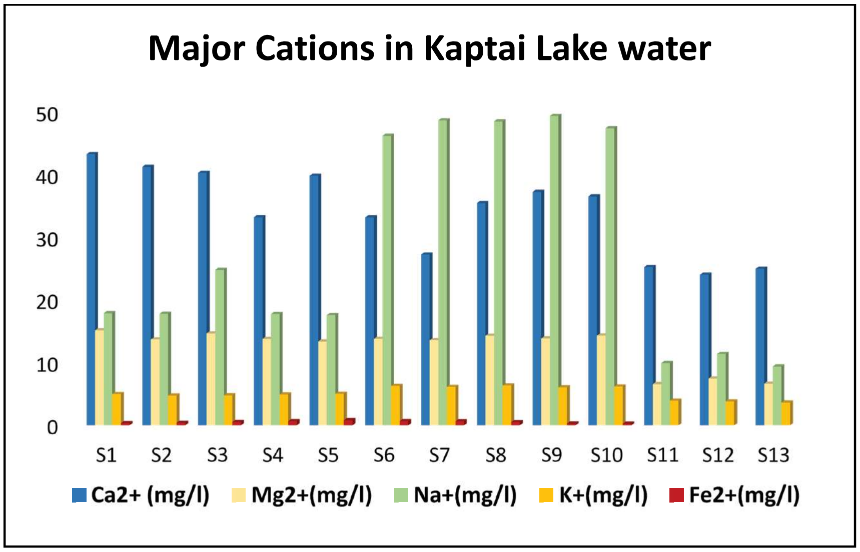

Figure 11: Sample Wise Distribution of Cations in Kaptai Lake Water

Ca^{2+} is the dominant cation within the studied segment of the Kaptai Lake. Followed by Mg^{2+} and Na^{+}. The cationic dominance in the studied segment of the Lake is in the order of $Ca^{2+} > Na^{2+} > Mg^{2+} > K^{+} > Fe^{2+} > Mn^{2+}$. The value of Ca^{2+} is the highest in the S1 and the lowest in S12. S1 and S11 show the highest and lowest value of Mg^{2+} respectively. For Na^{+} the highest concentration was found in S9 and the lowest concentration was found in S13. The value of K^{+} is the highest in S8 and the lowest in S13. The concentrations of Fe^{2+} and Mn^{2+} are negligible in all the sampling points.

HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- etc. are the major anions found in the selected segment of the Kaptai Lake.

The value of HCO_3^- ranges from 91.50 to 221.13 mg/l with an average value of 171.86 mg/l. The value of Cl^- ranges from 5.02 to 26.21 mg/l averaging at 12.03 mg/l and much lower than the BDWL of DPHE for Cl^- that is 150-600 mg/l. The value of SO_4^{2-} ranges from 0.61 to 52.15 mg/l with an average value of 25.19 mg/l and very much lower than the BDWL for SO_4^{2-} (400 mg/l). The value of NO_3^- ranges from 0 to 2.29 mg/l with an average value of 0.23 mg/l and falls within the BDWL that is <1 mg/l. The key statistical attributes and their relationship with BDWL value are shown in the table 5.

The sample wise distribution of Anions can be given by the following bar diagram **(**Fig. 12**)**

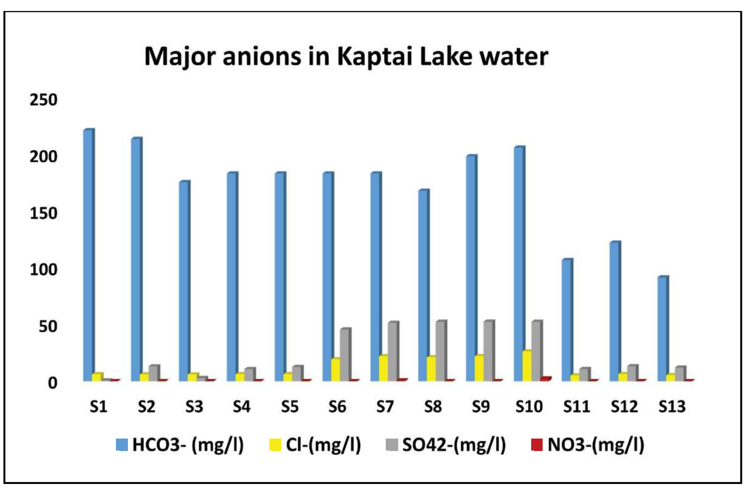

Figure 12: Sample Wise Distribution of Anions in Kaptai Lake Water

HCO_3^- is the dominant anion within the studied segment of the Kaptai Lake. Followed by SO_4^{2-} and Cl^-. The anionic dominance in the studied segment of the Lake is in the order of $HCO_3^- > SO_4^{2} > Cl^- > NO_3^-$. The value of HCO_3^- is the highest in the S1 and the lowest in S13. S10 and S1 show the highest and lowest value of SO_4^{2-} respectively. For Cl^- the highest concentration is found in S10 and the lowest concentration was found in S11. The concentration of NO_3^- is considerably low in all the sampling points.

Discussion

Water quantity of Kaptai Lake gradually decreased and then increased during the studied period. The probable cause for increasing and decreasing water in the lake are rainfall, the mode of dam operation, sedimentation, climate change, land use changes etc. Heavy rainfall can lead to an increase in water inflow and as a consequence the water level in the lake rises and opposite happens when there is low/no rainfall (Mohamed and Savenije, 2014). Releasing water downstream or holding it back, can directly affect the water quantity in Kaptai Lake (Wang et al., 2017). The deposition of sediment reduces the lake's capacity to hold water, resulting in a decrease in water quantity (Xie et al., 2017). Changing weather patterns, such as variations in rainfall intensity, increased evaporation rates, or changes in the flow of rivers feeding the lake, can all contribute to fluctuations in water quantity (Mohamed and Savenije, 2014). Changes in land use, such as deforestation, urbanization, or agricultural practices, can affect the hydrological cycle and consequently the water quantity in Kaptai Lake (Xie et al., 2017).

Chlorophyll-a is not equally distributed in the lake. The outcome of the analysis based on both in situ measurements and image data suggests that the lake's trophic status ranges from mesotrophic to eutrophic, as indicated by the association of Trophic Status and Chlorophyll-a Concentration in Lakes (Boyd, 2015; Patra et al., 2017). Chlorophyll-a can be changed for various reasons i.e. excessive nutrients, particularly nitrogen and phosphorus, can enter the lake through agricultural runoff, sewage discharge, and industrial waste (Smith et al., 1999). Sediments, rich in nutrients, can be carried into the lake through runoff. These nutrients contribute to the growth of algae and subsequently elevate the chlorophyll-a levels. If untreated sewage and wastewater from human settlements, industries, or agricultural activities are discharged directly into the lake, it can introduce organic matter and nutrients, which support the growth of algae and increase chlorophyll-a concentrations (Chapman, 2021). Changes in precipitation patterns and temperature can influence the nutrient load entering the lake, alter the hydrological cycle, and affect the lake's water temperature (Schindler, 2009). These changes can create more favorable conditions for algal blooms and increase chlorophyll-a concentrations.

Similar to Chlorophyll-a turbidity is not equal everywhere. Turbidity can be changed for various reason. Erosion of soil from the surrounding land can introduce sediment and other particulate matter into the lake, increasing turbidity (Cao, et al., 2017). Human activities such as construction, mining, and urban development near the lake can result in increased turbidity (Donohue and Molinos, 2009). Industrial operations near the lake may release various pollutants and suspended solids into the water, leading to increased turbidity (Raburu and Okeyo-Owuor, 2006). Algal growth can increase turbidity when the algae die off and decompose, releasing organic matter into the water. Natural events like heavy rainfall, flooding, and landslides can result in elevated turbidity levels in the lake. Improperly treated or untreated sewage and wastewater discharge can introduce pollutants and suspended solids into the lake. This can significantly impact water quality, including turbidity. To validate the image retrieved values in situ field measurements were taken and regressed with that of the image retrieved values. The linear regression analysis confirms about 62.1% validation for chlorophyll-a and about 69.7% validation for turbidity **(**Fig. 13 & 14**)**.

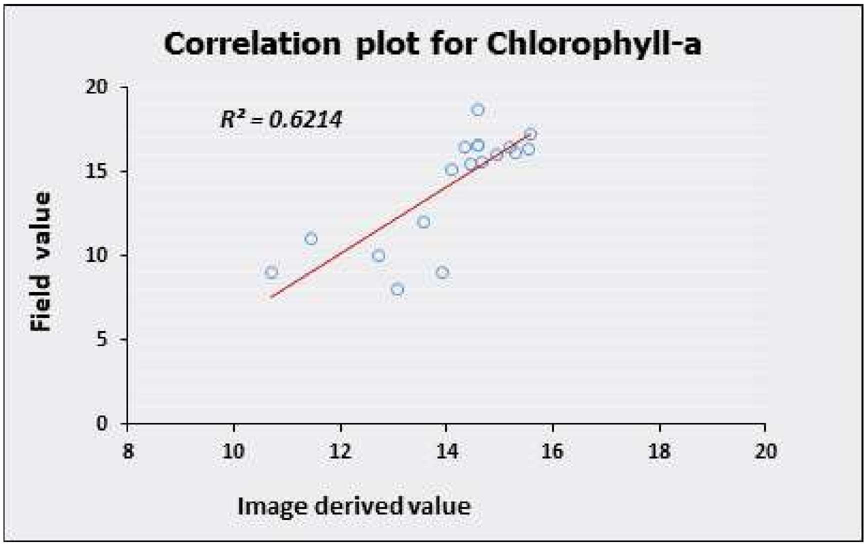

Figure 13: Correlation between Image Retrieved and Field Measured Values of Chlorophyll-a

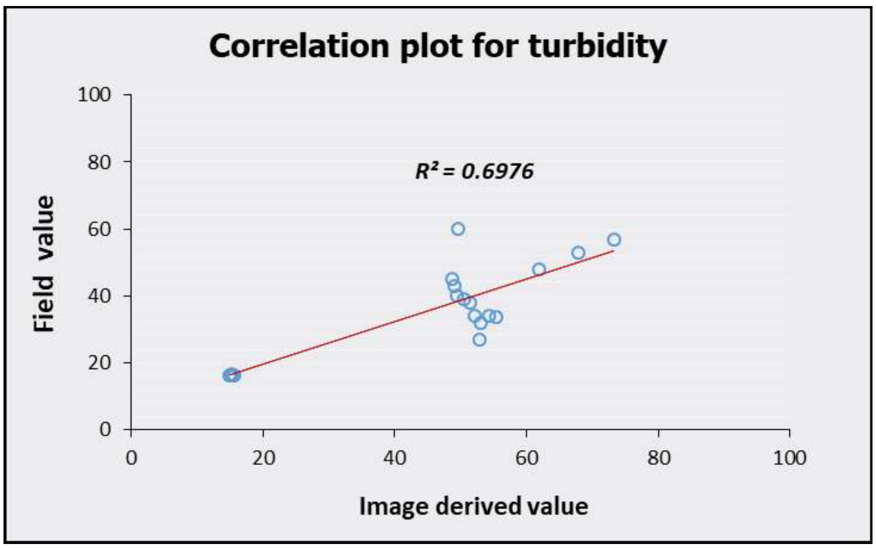

Figure 14: Correlation among Image Retrieved and Field Measured Values of Turbidity

Although the image retrieved and field values of the quality parameters have shown strong positive correlation there might have some limitations behind this. First of all the field sampling area was confined to a specific segment of Kaptai lake because of some accessibility and security issues and the accuracy of water quality parameters derived from remote sensing may be lower than direct field measurements. Factors such as cloud cover, sensor resolution, and the complexity of interpreting satellite imagery in mixed land-water areas can reduce the precision of remote sensing data (Swain et al., 2023). But above all these limitations the strong correlation has been found in many other studies assessing lake water quality based on satellite image analysis because the lake water remains calm and quiet and have not been severely affected by water influx like river and other surface water bodies.

CONCLUSIONS

Lake water quality monitoring is essential to ensure the sustainability of freshwater resources, protect aquatic ecosystems, and safeguard public health by detecting pollution and assessing environmental changes. The prime goals of the current research are to assess the spatiotemporal variation in extent and quality of Kaptai Lake water through satellite image processing and to validate the image derived parameters based on field based observation. The methodological flow of the study encompass satellite image processing, in situ field measurements, laboratory analysis and statistical analysis. The study utilized Landsat TM/OLI and Sentinel 2B satellite images for assessing the lake water extent and quality (turbidity & Chlorophyll-a) respectively. In situ field measurements of quality parameters such as turbidity and Chlorophyll-a were taken for ground truth validation. The field measurements of physico-chemical parameters such as pH, Ec, temperature and laboratory analysis of hydrochemical parameters such as major cations and anions have been performed to assess the contemporary water condition. The lake's water extent has been decreased by approximately 3% from 1989 to 2010 and increased by about 5% from 2010 to 2021. Changing rainfall patterns, dam operations, sedimentation, and land use changes can be attributed for this. Chlorophyll-a concentration and turbidity show seasonal variation with higher turbidity in post-monsoon. The trophic status of the lake can be concluded as mesotrophic to eutrophic based on the aforementioned parameters. The study found that nutrient enrichment from untreated sewage, agricultural runoff, and algal growth affect chlorophyll-a levels, while development activities, excessive rainfall, and sedimentation influence turbidity. Image derived and field obtained values show strong positive correlation for both Chlorophyll-a and turbidity. The average value of physico-chemical parameters pH, EC and temperature are 7.55, 119.85 µS/cm and 22.17 °C respectively. Hydrochemical parameters, cations and anions varies in the order of Ca^{2+} > Na^{2+} > Mg^{2+}>K^{+} > Fe^{2+} >Mn^{2+} and HCO_3^- > SO_4^{2} > Cl^- > NO_3^- respectively where all complying with the BDWL. The subtle variation of the physico-chemical and hydrochemical parameters throught the lake implies that they are not interlinked with the Chlorophyll-a and turbidity variation. The results of this study can enhance knowledge and management of Kaptai Lake's water quality by providing an efficient approach for monitoring and the sustainable management of the lake's ecosystem.

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