

MONSOON-DRIVEN DYNAMICS OF CHLOROPHYLL-A: EVALUATING PHYSICAL AND PHYSICO-CHEMICAL CONTROLS IN THE MEGHNA ESTUARY, BHOLA DISTRICT

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Abstract

The Meghna estuary, vital for Bangladesh's fisheries, transportation, and coastal livelihoods, faces threats from nutrient loading, sedimentation, and upstream effluents. This necessitates systematic water quality monitoring to ensure ecological and economic sustainability. Hence, this study assessed physical, physicochemical, and biogeochemical parameters during the monsoon, using in situ CTD measurements and laboratory double-extraction spectrophotometric analysis for chlorophyll and nutrients. Temperatures averaged 30.6°C, exceeding national standards with minimal spatial variation, while turbidity increased from 104.8 NTU at the surface to 149.1 NTU at 5 m depth. In addition, pH (6.9-7.2) and dissolved oxygen (DO) (4.0-5.2 mg/L) stayed within acceptable ranges with a vertical decreasing pattern, lowest at the most turbid station. Chl-a averaged 0.87 µg/L at the surface and 0.39 µg/L at depth, peaking at Station 3 (1.55 µg/L surface, 0.54 µg/L depth) with high phosphate and low turbidity. Chl-a strongly correlated with DO ($r = 0.99$ surface, $r = 0.95$ depth) and phosphate ($r = 0.71$ surface, $r = 0.85$ depth), reflecting nutrient-driven productivity. Ammonia and silicate concentrations rose upstream and mid-estuary, and correlated negatively with Chl-a concentration. While phosphate levels peaked downstream, exceeding national

Keywords and phrases: Meghna estuary, chlorophyll-a, dissolved oxygen, nutrient dynamics, phosphate, ammonia, silicate.

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standards and positively correlating with chl-a, indicating a potential threat of eutrophication due to nearby anthropogenic activities. Eutrophication might initiate dense algal blooms that, upon decomposition, severely deplete dissolved oxygen and create hypoxic or anoxic “dead zones” where most aquatic life cannot survive. These findings emphasise the need for continuous monitoring and coordinated management to maintain the estuary’s ecological health and economic role.

1. Introduction

Rivers originate, evolve over time, and both sustain ecosystems and pose risks [1]. Hence, a river’s robust health is instrumental in ensuring sustainable ecological balance and economic prosperity along its banks, as its vitality depends on having optimum productivity while maintaining minimal pollution levels [2], [3]. Chl-a and nutrient concentrations are the indicators of the aquatic health of a riverine system, where chl-a is a proxy for phytoplankton biomass, representing the base of the aquatic food web, and nutrient levels (e.g., nitrogen, phosphorus, etc.) signal whether the environmental conditions are favourable to healthy production or are likely to trigger eutrophication [4], [5]. Hence, monitoring these parameters helps scientists understand seasonal variations, detect pollution impacts, and evaluate primary productivity [6], [7].

Bangladesh is a riverine country with almost 230 rivers flowing through it, 54 of which are shared with India, and 3 are shared with Myanmar [8]. They serve for numerous essential purposes, such as transportation, irrigation, food source, etc [9]. As a developing country, rivers in Bangladesh are facing severe quality degradation due to the pressure of unsustainable urbanisation, industrialisation and agricultural activities [10]. Major contaminations to rivers are untreated industrial effluents, municipal wastewater, and agricultural runoff, leading to high levels of pollutants such as heavy metals, pesticides, and faecal coliforms [11]. Many rivers in urban areas, including Karnaphuli, Buriganga, Turag, and Korotoa, exhibit critical levels of contamination and a very low level of DO, which eventually end up being merged with the GBM system [12]. Additionally, according to Hasan et al. [13], physicochemical parameters and heavy metal concentrations often exceed WHO limits, posing non-carcinogenic and potential carcinogenic risks to human health. Though nutrients are crucial for river productivity, many rivers are also reported to have either very low or very high concentrations of necessary nutrients, which threatens the ecological balance and health of the related rivers [12]. Especially, higher nutrient concentration than required can lead to eutrophication, followed by algal blooms and toxic river water [14].

Hence, it is immensely significant to regularly monitor the water quality of rivers and estuaries in Bangladesh. However, very few studies such as Hasan et al. [15], Hasan et al.[13], Kamal and Khan [16], Padmavathi and Satyanarayana [17], Rahaman et al. [18], Rahaman et al. [19], Sadi et al. [20], Uddin et al. [21], Uddin and Jeong [12] and Uddin et al. [22] has

conducted some research involving riverine nutrients and chlorophyll concentration in this country so far. Here, Sadi et al. [20] assessed the water quality and its impact on the chl-a in the Karnaphuli River estuary. They found an increasing trend in chl-a and ammonia from the upstream estuary toward the sea. According to several other studies, estuaries there show a decrease of nutrients from the estuarine mouth toward the sea [17], [21]. They have also reported an irregular temporal and spatial distribution of nitrate, nitrite, phosphate, ammonia and silicate while demonstrating the highest nutrients peak during pre-monsoon and lowest during monsoon [18], [21].

However, it is found to be unlike in the case of the central coast of Bangladesh, such as the lower Meghna estuary, which is the study area of this research. Though this is the most important river of Bangladesh, being the combined outlet of the GBM (Ganges, Brahmaputra and Meghna) river system, collecting water from almost 1.758 million sq. km catchment area of India, Bangladesh and Nepal [23] and receives a vast amount of nutrient input from the upstream and releases it into the Bay of Bengal. Hence, this is famously known as a rich fishing and fish-breeding area [21]. Unfortunately, the estuary is scientifically quite unexplored, and no studies in the Meghna estuary have conducted any assessment on the chlorophyll concentration or looked into the impacts of nutrients on the river production. Though this estuary provides essential provisioning services like food from the Hilsha fishery, regulatory services such as nursery habitats, and cultural services, it has drawn a much minimal attention to its health and quality assessment [24]. In this current study, we will assess the water quality of the lower Meghna estuary near Bhola district and find its impacts on the chl-a distribution during the monsoon period in August 2024.

The remainder of this paper is arranged as follows. Section 2 describes the methodology; the methods used to measure in situ physicochemical parameters, as well as laboratory processes of chl-a and nutrients analysis. Section 3 discusses the findings: the distribution of physical, physicochemical and biological parameters, their correlation, and impacts on the ecosystem and ecology. Finally, Section 4 concludes this study.

2. Methodology

2.1. Study area

The Meghna estuary empties primarily through four canals into the Bay of Bengal, which are Hatia, Shahbazpur, Tentulia, and Bamni. This study collected and analysed water along the Shahbazpur canals, close to the Char-fashion Upazila of Bhola District. At five evenly spaced stations along the 51.50 km waterway (Figure 1), samples were drawn from both the surface and a depth of 5 m. The sampling was done during the monsoon season in August 2024.

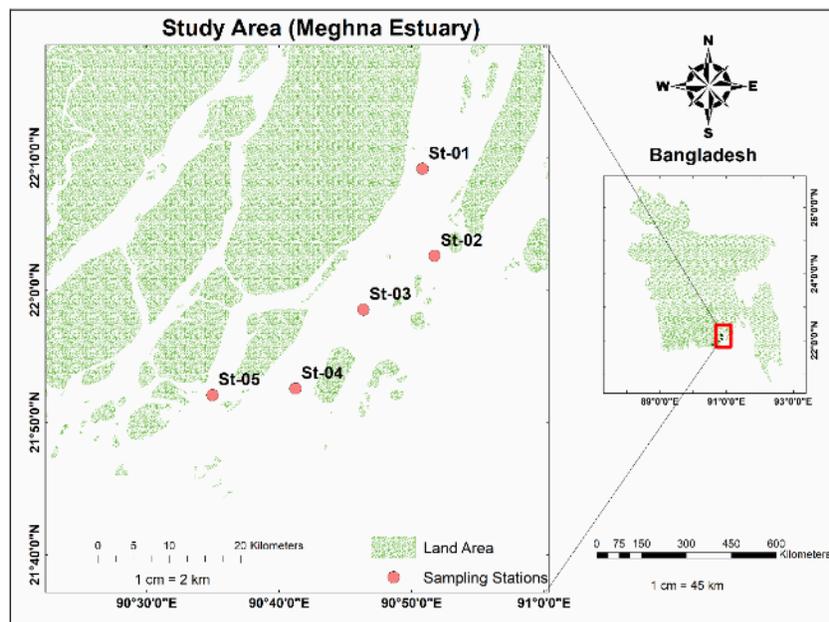


Figure 1. The Meghna estuary with depiction of sample collection points marked with red dots. Here, S indicates Stations, e.g., S1 is station 1.

2.2. Sampling and data collection

Numerous physicochemical parameters, such as temperature, pH, turbidity, DO, ammonia, silicate, phosphate, and chl-a were measured for this study during the monsoon season in August 2024. The monsoon season was specifically emphasised in this study, as it represents the period of peak annual river discharge and nutrient influx, thereby offering greater clarity on the river's influence on estuarine water quality. A sea-bird CTD (SBE 19 Plus) was used to record the temperature, pH, turbidity, and DO through the water column at the selected locations.

In addition, in situ water samples were collected for nutrient and chl-a analysis from both the surface and 5m depth during low-tide conditions. A clean bucket, after being rinsed with ambient river water, was utilised for fetching a surface sample, while a Niskin Bottle was used for collecting water from the depth [25]. In case of lowering the Niskin, the rope was marked in every meter to indicate the real-time depth of that bottle. Samples were collected in plastic bottles, which were also rinsed with ambient river water, followed by storing in a black plastic bag to avoid further photosynthesis in the sampled water [26]. Then, the samples were stored at -20°C until they reached the laboratory for analysis [27].

2.3. Quality assurance

For physical parameter measurements with CTD, the necessary sensors were attached and calibrated before deploying the machine to ensure accurate measurement of these parameters. Besides, buckets and Niskin bottles were cleaned every time with ambient water before

collecting samples to ensure no contamination from earlier stations or any other sources. During laboratory analysis, a blank test was conducted to confirm the full and accurate functionality of the Continuous Flow Analyser. Then, each sample was tested three times to obtain average values for each station, ensuring the accuracy of the measurement.

2.4. Chlorophyll-a analysis

To quantify chl-a, water samples were put through the double extraction method for pigment extraction. First, a 0.45 μm cellulose nitrate filter paper was positioned on a filter holder attached to a 500 mL vacuum bottle, and approximately 300 mL of water was filtered using a suction pump with a sucking power <30 kPa [28]. After that, the filter paper was then gently rolled with forceps and transferred to an extraction tube. Then, 4 mL of 94% ethanol, pre-heated to 75-80 $^{\circ}\text{C}$, was added to the tube and maintained at that temperature for 2-3 minutes. Then, the extract was transferred to another tube, and an additional 4 mL of pre-heated ethanol was added to the original tube. After another 2-3 minutes at 75-80 $^{\circ}\text{C}$, the filter paper was thoroughly squeezed, and the second extract was combined with the first, yielding 8 mL of extract. This combined extract was filtered through a syringe fitted with a 0.45 μm filter, and extra ethanol was added to adjust the final volume to 10 mL. For fluorescence analysis, a 10 mL cuvette was filled with the extract, and its absorbance was measured at 665 nm and 750 nm using a spectrophotometer, with 10 mL of pure ethanol as the blank. Finally, 0.035 mL of 2M HCl was added to the extract, and the absorbance at 665 nm and 750 nm was measured again. Then the following equation is used to determine the concentration of chl-a in the sample: [28]

$$\text{Chl} - a \left(\mu \frac{\text{g}}{\text{L}} \right) = 29.1 \times (A - Aa) \times \frac{v}{V} \times d.$$

Here,

$$A = A_{665} - A_{750},$$

$$Aa = Aa_{665} - Aa_{750},$$

A_{665} = Absorbance at 665nm before adding 2M HCl,

A_{750} = Absorbance at 750nm before adding 2M HCl,

Aa_{665} = Absorbance at 665nm after adding 2M HCl,

Aa_{750} = Absorbance at 750nm after adding 2M HCl,

v = Extract volume of the pigment in ml,

V = Filtered volume of sample water in liter, and

d = Path length of the cuvette used to measure absorbance in cm.

2.5. Nutrient analysis

Analysis was performed using a Skalar San++ Continuous Flow Analyser configured to process ammonia, silicate, and phosphate simultaneously [29]. Although the system is capable of nitrite and nitrate measurement; however, contamination issues were encountered during the survey and therefore, precluded their methods here. Each nutrient channel uses a dedicated set of reagents. The reagent and sample streams are delivered together through a manifold, where they are mixed and heated before passing into a flow cell for measurement. Air bubbles between sample segments improve mixing and prevent carry-over contamination. Within the flow cell, the reagents chemically react with the analyte to produce a coloured compound, and its concentration is determined by measuring the absorbance at the appropriate wavelength [29], [30]. Data acquisition and control were managed through the Skalar Interface linked to the FlowAccess software.

All reagents were prepared in the laboratory following the manufacturer's protocol, using analytical-grade chemicals weighed on calibrated balances. Solutions were stored in acid-washed polyethene containers and brought to volume with ultrapure water produced by a Smart2Pure system [31]. Reagent compositions are provided in Table 1. Reagent storage time was following the Skalar methods: most solutions remained stable for up to 1 week, while the silicate, ammonium heptamolybdate and oxalic acid reagents could be stored for up to 1 month. Nevertheless, all reagent batches were freshly prepared at the start of the analysis.

Table 1. Sampling protocols, instrument tubing size, and reagent formulations for nutrient analyses (ammonia, silicate, phosphate) on the Skalar San++ Continuous Flow Analyser

Sampling		
	Sample tubes	50 mL Falcon tubes (rinsed 3 × with sample water before filling)
	Primary sample analysis	Within 12 h of sampling – 20°C
	Replicate samples	
Analysis		
	Auto-sampler size	300 cups
	Auto-sampler cup size	10 mL
	Baseline wash	Artificial seawater
	Lab temperature	23 °C
Reagents (gL^{-1} or $mL\ min^{-1}$)		
	Artificial seawater	35 g sodium chloride; 0.5 g sodium hydrogen carbonate

For ammonia analysis, samples were first treated sequentially with EDTA-NaOH and tartrate-citrate buffer solutions, then reacted with phenol and hypochlorite to form the indophenol blue chromogen. Nitroprusside catalysis and an H_2SO_4 scrubber removed residual air, and the absorbance of the resulting dye was measured at 630 nm [32].

Silicate was quantified by acidifying the sample with sulfuric acid and adding ammonium heptamolybdate to generate molybdosilicic acid, which was reduced by L(+)-ascorbic acid to a blue complex read at 810 nm; oxalic acid was included to eliminate phosphate interference.

Phosphate determination involved reaction with ammonium heptamolybdate and potassium antimony(III) oxide tartrate in acidic medium to form an antimony-phosphomolybdate complex, subsequently reduced by L(+)-ascorbic acid to an intense blue chromophore measured at 880 nm [31], [33].

Table 1. Continued

Ammonia	
Sample tubing size	1.40 mL min ⁻¹
Phenol Reagent	83g Phenol; 40g NaOH
Reagent tubing size	0.23 mL min ⁻¹
Sodium Hypochlorite	200 mL Sodium Hypochlorite
Reagent tubing size	0.23 mL min ⁻¹
Sodium Nitroprusside	0.5g Sodium Nitroprusside in 1L distilled water
Reagent tubing size	0.23 mL min ⁻¹
Air Scrubber	139 mL sulfuric acid diluted to become 1L
Reagent tubing size	0.23 mL min ⁻¹
Wash solution	3 mL Brij solution
Reagent tubing size	1.00 mL min ⁻¹
Silicate	
Sample tubing size	1.40 mL min ⁻¹
Sulfuric acid solution	20 mL sulfuric acid
Reagent tubing size	0.23 mL min ⁻¹
Ammonium heptamolybdate	20 g ammonium heptamolybdate
Reagent tubing size	0.42 mL min ⁻¹
Oxalic acid	44 g oxalic acid
Reagent tubing size	0.42 mL min ⁻¹
L(+)-ascorbic acid	40 g ascorbic acid
Reagent tubing size	0.32 mL min ⁻¹

Phosphate

Sample tubing size	1.40 mL min ⁻¹
Ammonium heptamolybdate	0.23 g potassium antimony(III) oxide tartrate; 70 mL sulfuric acid; 6 g ammonium heptamolybdate; 2 mL FFD6
Reagent tubing size	0.42 mL min ⁻¹
L(+)-ascorbic acid	11 g ascorbic acid; 60 mL acetone; 2 mL FFD6
Reagent tubing size	0.42 mL min ⁻¹

2.6. Statistical and spatial analysis

Pearson correlation coefficients were computed to quantify linear relationships between all the parameters, including chl-a, nutrient concentrations (ammonia, silicate, phosphate) and key physicochemical parameters (e.g. salinity, temperature, dissolved oxygen) at both the surface and deepwater of the Meghna Estuary. Pairwise correlations (r) were calculated using standard Pearson methods, and statistical significance was assessed at $p < 0.05$. This allowed identification of which environmental parameters showed strong coupling with nutrient and productivity dynamics [34].

Furthermore, spatial distributions of nutrient and chl-a concentrations were mapped using inverse distance weighted (IDW) interpolation in ArcGIS Spatial Analyst. IDW estimates values at unsampled locations based on the proximity-weighted average of nearby measurements, assigning greater influence to closer points [35]. Here, interpolation settings were optimized via a variable search radius to include the nearest 2-3 points and a power parameter of 2, achieving minimal interpolation error while preserving local variability [35].

3. Results and Discussion

In-situ water samples collected from the Meghna estuary near Bhola district were analysed for both physical, physicochemical and biogeochemical parameters. These measured parameters are shown in Table 2 and also depicted in various charts and figures added later in this paper.

3.1. Physical parameters distribution

Physical parameters such as temperature, salinity, and turbidity critically determine a river's ecological status and habitat structure. To evaluate the physical health of the Meghna estuary during the monsoon season (August 2024), we measured water temperature and

turbidity at five evenly spaced stations over a 51.50 km pathway along the Shahbazpur Canal, sampling both at the surface and at 5m depth.

The mean water temperature was 30.62°C at the surface and 30.60°C at 5 m depth, slightly exceeding the national river-water temperature standard [36]. Temperature exhibited the least spatial variability of all measured parameters (Figure 1a; Table 3), ranging from 30.49°C to 30.75°C at the surface and from 30.50°C to 30.74°C at depth.

Table 2. Measured physicochemical parameters along with Nutrients and chl-a concentration across five stations

Stations	1		2		3		4		5	
Depth	0 m	5 m	0 m	5 m	0 m	5 m	0 m	5 m	0 m	5 m
Temperature (°C)	30.75	30.74	30.61	30.60	30.65	30.57	30.61	30.60	30.49	30.50
pH	7.20	7.20	6.90	6.90	7.10	7.00	7.20	7.00	7.10	6.90
Turbidity (NTU)	136.30	212.81	133.01	179.59	77.03	109.78	107.95	112.09	69.90	131.18
DO (mg/L)	4.30	4.00	4.60	4.40	5.20	4.70	4.50	4.30	4.50	4.10
Ammonia (mg/L)	1.88	2.21	0.99	2.01	0.10	0.39	0.31	1.81	1.09	2.58
Silicate (mg/L)	451.61	336.18	276.82	215.10	148.67	189.83	245.93	217.23	394.11	286.45
Phosphate (mg/L)	9.34	8.12	11.17	10.38	11.55	11.89	11.35	10.56	10.47	7.95
Chlorophyll-a (mg/L)	0.49	0.32	0.78	0.39	1.55	0.54	0.78	0.36	0.58	0.34

Turbidity increased with depth, a pattern also observed in the Karnaphuli River of southern Bangladesh [20]. Surface turbidity varied between 69.90 and 136.30 NTU, whereas 5m depths registered values from 109.78 to 212.81 NTU (Tables 2 and 3). The overall mean turbidity was 104.84 NTU at the surface and 149.09 NTU at depth, both substantially above the national standard [36].

The elevated temperature and turbidity levels observed in the Meghna estuary during the monsoon season have significant implications for its ecosystem, biology, and environmental health. Water temperatures exceeding 30°C can elevate metabolic rates in aquatic organisms, potentially causing thermal stress to fish and invertebrates adapted to cooler conditions [37], [38]. Hence, this is a matter of concern for the Meghna Estuary as it may alter species distributions, reduce biodiversity, and affect spawning cycles critical to fishery productivity [39].

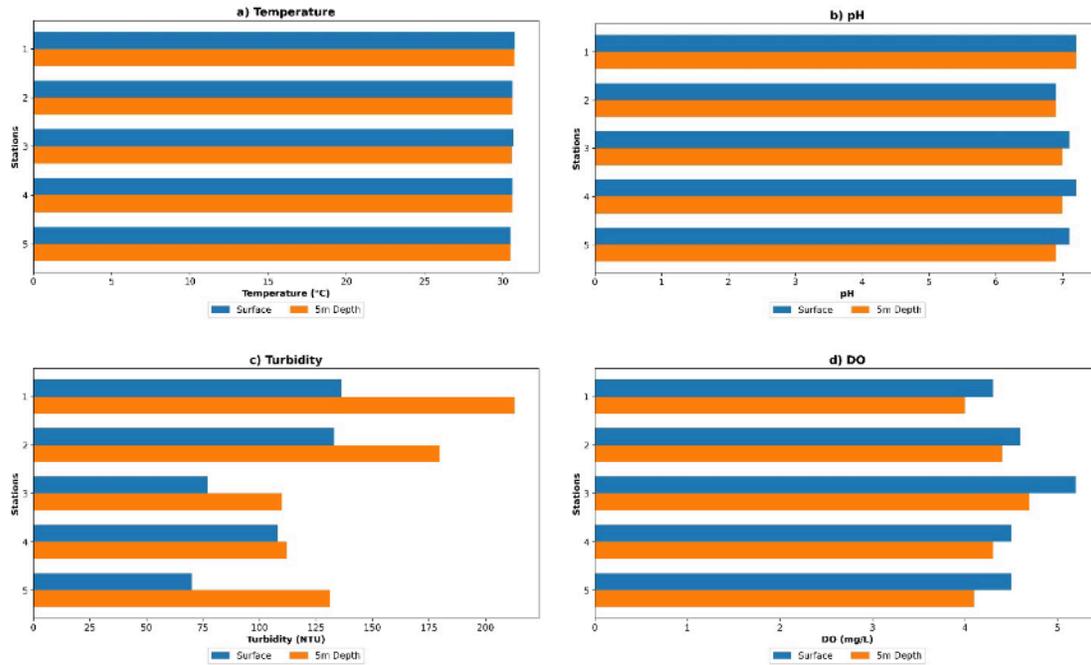


Figure 2. Physical and Physicochemical parameters, such as (a) Temperature, (b) pH, (c) Turbidity, and (d) DO, over different stations in both surface (blue) and 5m depth (orange).

In addition, monsoon-driven sediment transport intensifies the high turbidity in this region. This, consequently, reduces light penetration into the water column [40], eventually limiting the primary productivity through photosynthesis by phytoplankton and submerged aquatic vegetation. Hence, this reduced primary productivity can cascade through the ecosystem, decreasing food availability for fish and other aquatic species, ultimately impacting local fishing communities that rely on the Meghna estuary as a nursery ground and fishing hub [41].

Besides, elevated turbidity, caused by suspended solids that absorb solar radiation, can further raise water temperature [42]. Consistent with this mechanism, the highest turbidity values, in both surface and deeper water, coincided with the highest temperatures at Station 1 (Table 1; Figure 2a, c). Finally, temperature and turbidity exhibited moderately positive correlations, with Pearson's $r = 0.65$ at the surface and $r = 0.75$ at depth (Tables 4 and 5). This combined effect of these parameters warrants attention, particularly during the monsoon when river flow and sediment loads peak [43].

Table 3. Maximum, Minimum, Mean and Standard Deviation of parameters with a comparison to the respective national standard for physical and physicochemical parameters [36] and chl-a [18]

Parameters	Water at the Surface			Water at 5 m			Standard Values
	Minimum	Maximum	Mean±SD	Minimum	Maximum	Mean±SD	
Temperature	30.49	30.75	30.62±0.09	30.50	30.74	30.6±0.09	20-30
pH	6.90	7.20	7.1±0.12	6.9	7.2	7±0.12	6.5-8.5
Turbidity	69.90	136.30	104.84±30.77	109.782	212.8131	149.09±45.35	10
DO	4.30	5.20	4.62±0.34	4	4.7	4.3±0.27	4.0-6.0
Ammonia	0.10	1.88	0.87±0.71	0.39	2.58	1.8±0.84	0.5
Silicate	148.67	451.61	303.43±120.57	189.83	336.18	248.96±60.54	-
Phosphate	9.34	11.55	10.78±0.9	7.95	11.89	9.78±1.7	6
Chlorophyll	0.49	1.55	0.87±0.4	0.316	0.535	0.39±0.09	0.24-3

3.2. Physicochemical parameters distribution

Physicochemical parameters like pH, DO, nitrate, silicate, ammonia, and phosphate serve as vital signs of aquatic ecosystem health, shaping biological processes and fishery productivity in the Meghna estuary [44]. During the monsoon season, the estuary showcased a stable pH range of 6.9-7.2, aligning with national standards and supporting aquatic life, while DO levels averaged 4.62 mg/L at the surface and 4.30 mg/L at depth-adequate but slightly reduced in warmer, turbid waters [42]. However, nutrient levels raised concerns: phosphate averaged 10.78 mg/L at the surface, far exceeding guidelines, and ammonia peaked at 2.58 mg/L at depth, alongside elevated silicate concentrations [36], signalling risks like eutrophication and toxicity that could disrupt the food web.

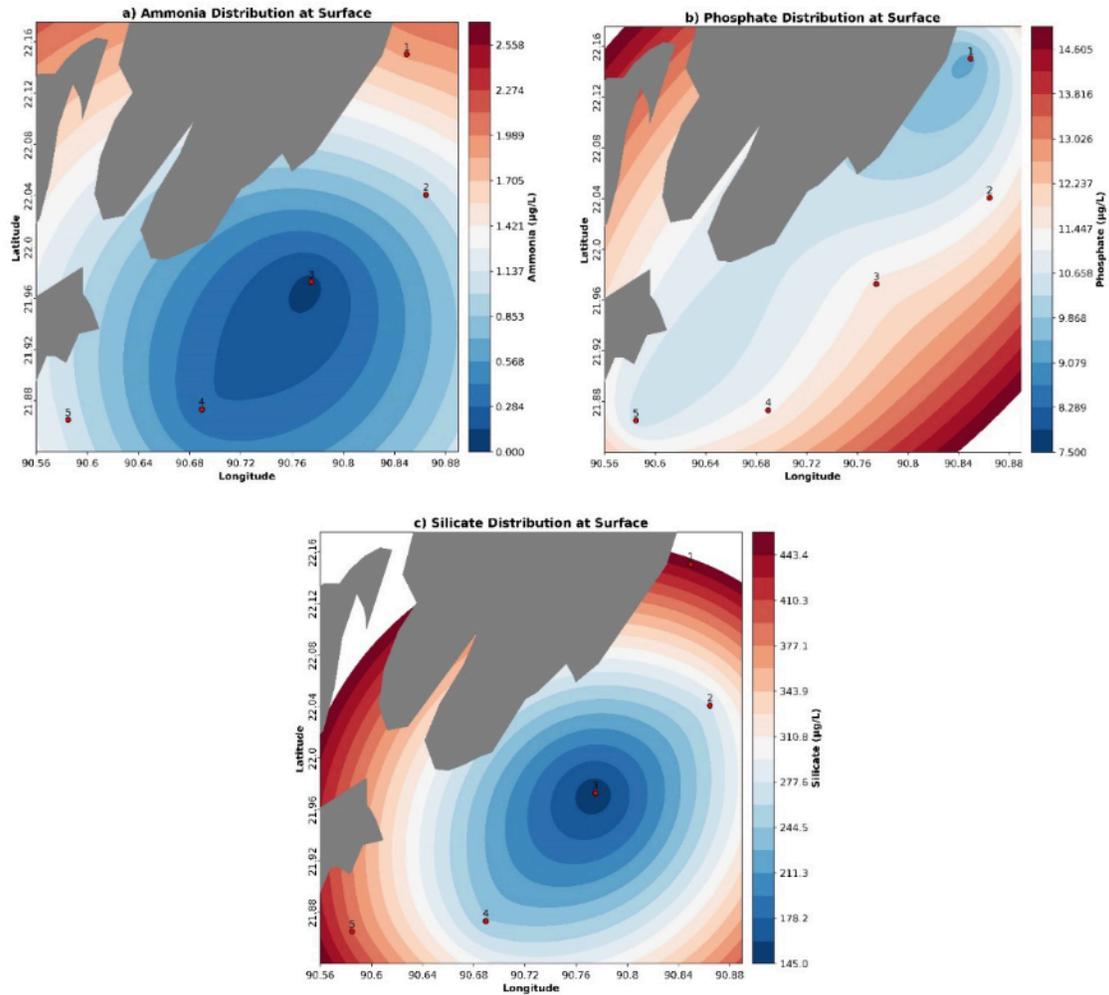


Figure 3. Nutrients, such as (a) Ammonia, (b) Phosphate, and (c) Silicate, distribution at the surface over 5 stations. Here, red dots represent the individual stations.

These conditions paint a dual picture of the Meghna estuary. Firstly, it is a nutrient-rich hub driving primary productivity. Secondly, it is also a vulnerable ecosystem teetering on imbalance. The high phosphate levels, strongly correlated with DO, boost the estuary's role as a thriving fishery [41], [45]. In addition, the higher concentration of phosphate than the national standard is putting risks of algal blooms in that region, if other parameters are favourable. However, the excess ammonia and silicate are limiting the growth of aquatic organisms and long-term stability [46], [47]. This delicate balance underscores the estuary's ecological and economic importance, as its productivity supports livelihoods dependent on its fisheries [48].

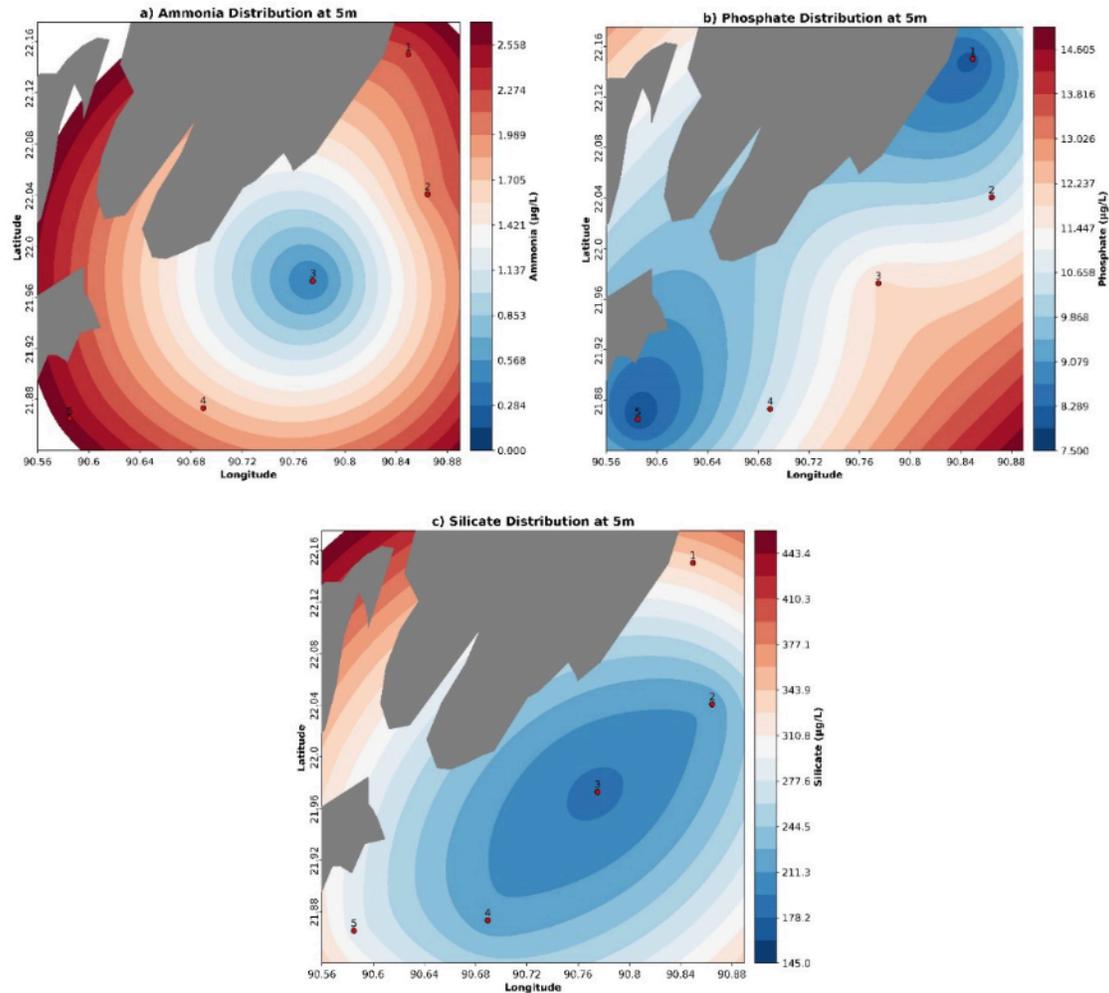


Figure 4. Nutrients, such as (a) Ammonia, (b) Phosphate, and (c) Silicate, distribution at 5m depth over 5 stations. Here, red dots represent the individual stations.

To sustain this vital ecosystem, ongoing monitoring and targeted management are critical. The stable pH and sufficient DO provide a solid foundation [49], [50], but the elevated nutrient demand requires intervention to prevent ecological tipping points like algal blooms or oxygen depletion [51], [52]. By maintaining this balance, the Meghna estuary can continue to thrive as a productive and sustainable aquatic environment.

3.3. Chlorophyll-a distribution

This study found that the distribution of chl-a in the Meghna estuary displayed a pronounced spatial gradient. Concentrations reached their maximum at Station 3, measuring 1.552 $\mu\text{g/L}$ at the surface and 0.535 $\mu\text{g/L}$ at a depth of 5 meters, and their minimum at Station 1, with 0.488 $\mu\text{g/L}$ at the surface and 0.316 $\mu\text{g/L}$ at 5 meters (Table 2). Across the estuary, mean chl-a levels were 0.87 $\mu\text{g/L}$ at the surface and 0.39 $\mu\text{g/L}$ at depth, marginally

surpassing the national minimum threshold (Table 3). This gradient suggests heightened phytoplankton productivity near the estuary mouth (Figure 5), likely attributable to nutrient-enriched freshwater inputs [53].

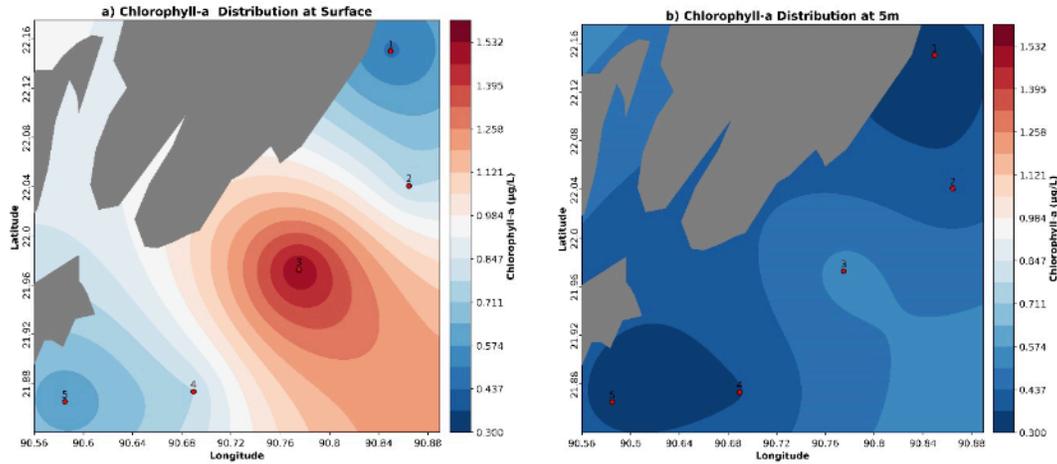


Figure 5. Chl-a distribution at (a) Surface and (b) at 5m depth over 5 stations. Here, red dots represent the individual stations.

Statistical analysis using Pearson's correlation coefficients demonstrated robust positive relationships between chl-a and DO, with values of $r = 0.99$ at the surface and $r = 0.95$ at depth, and between chl-a and phosphate, with $r = 0.71$ at the surface and $r = 0.85$ at depth (Tables 4 and 5). These correlations highlight phosphate's critical role in promoting phytoplankton proliferation, which subsequently elevates DO concentrations through photosynthesis, sustaining aerobic aquatic life integral to the estuarine food web and fishery resources [41], [45].

Table 4. Pearson Correlation of Nutrients and Physicochemical parameters at the surface water of the Meghna estuary. Here, correlation with a 0.05 significance level is indicated as bold numbers and p -values are given in italic font.

	Temperature	DO	pH	Turbidity	Chlorophyll-a	Ammonia	Silicate	Phosphate
Temperature	1	0.95	0.63	0.24	0.9	0.62	0.92	0.53
DO	-0.04	1	0.7	0.34	0	0.14	0.05	0.18
pH	0.3	-0.24	1	0.82	0.82	0.92	0.69	0.53
Turbidity	0.65	-0.54	-0.14	1	0.43	0.34	0.59	0.52
Chlorophyll-a	0.08	0.99	-0.14	-0.47	1	0.11	0.04	0.18
Ammonia	0.31	-0.76	0.06	0.54	-0.79	1	0.02	0.02
Silicate	0.06	-0.85	0.24	0.33	-0.89	0.93	1	0.02
Phosphate	-0.38	0.71	-0.37	-0.39	0.71	-0.94	-0.93	1

Conversely, ammonia and silicate exhibited significant inverse correlations with both chl-a and DO, potentially undermining estuarine productivity. Ammonia concentrations averaged 0.87 mg/L at the surface and 1.80 mg/L at 5 meters depth, exceeding the national threshold of 0.50 mg/L, and displayed strong negative correlations with chl-a ($r = -0.79$ at the surface; $r = -0.95$ at depth) and DO ($r = -0.76$ at the surface; $r = -0.90$ at depth) (Tables 4 and 5). Likewise, silicate levels averaged 303.43 mg/L at the surface and 248.96 mg/L at depth, showing negative correlations with chl-a ($r = -0.89$ at the surface; $r = -0.77$ at depth) and DO ($r = -0.85$ at the surface; $r = -0.92$ at depth). Elevated ammonia imposes a biochemical oxygen demand, depleting DO levels [54], while high silicate concentrations, indicative of suspended sediments, diminish light availability, thereby constraining photosynthetic activity.

Table 5. Pearson Correlation of Nutrients and Physicochemical parameters at the deeper water of the Meghna estuary. Here, correlation with a 0.05 significance level is indicated as bold numbers and p -values are given in italic font

	Temperature	DO	pH	Turbidity	Chlorophyll-a	Ammonia	Silicate	Phosphate
Temperature	1	0.57	0.05	0.14	0.59	0.91	0.43	0.78
DO	-0.35	1	0.54	0.32	0.01	0.04	0.03	0.01
pH	0.88	-0.37	1	0.37	0.71	0.95	0.31	0.68
Turbidity	0.75	-0.57	0.52	1	0.33	0.41	0.22	0.35
Chlorophyll-a	-0.33	0.95	-0.23	-0.56	1	0.01	0.13	0.05
Ammonia	0.07	-0.9	-0.04	0.48	-0.95	1	0.19	0.05
Silicate	0.47	-0.92	0.58	0.67	-0.77	0.69	1	0.02
Phosphate	-0.18	0.95	-0.25	-0.54	0.85	-0.87	-0.93	1

Overall, these dynamics reveal the estuary's delicate equilibrium. The nutrient inputs bolster its role as a vital fishery hub, supporting local livelihoods [48], yet excessive ammonia and silicate threaten aquatic habitats and reproductive processes [46], [47]. Effective management is essential to balance productivity and ecological health.

4. Conclusion

The Meghna estuary demonstrates clear evidence that during the monsoon season, its estuarine system depends heavily on freshwater inflow from upstream sources. This shapes the estuary's ecological health by delivering nutrients and sediments that drive productivity and biodiversity. Although temperatures both at the surface and below exceeded national guidelines, they displayed little spatial difference throughout the area. Water turbidity

increased markedly with depth, reflecting the intense influx of suspended solids during peak flow periods, which coincided with elevated temperatures at the most turbid station. Physicochemical indicators for pH and DO demonstrate suitable conditions, whereas oxygen levels decreased vertically while reaching their minimum points at turbidity and temperature hotspots. The analysis of nutrients showed rising levels of chl-a and phosphate from the river upstream to the mouth of the river due to monsoonal delivery that promoted primary productivity. The levels of ammonia and silicate simultaneously reached their highest point at the upstream and mid-estuarine positions, which caused negative effects on oxygen availability and phytoplankton abundance. In essence, strong positive correlations between chl-a, DO, and phosphate underscore the estuary's productive potential, while negative associations with ammonia and silicate highlight vulnerabilities. In addition, nutrient concentrations in the estuary, particularly phosphate, exceeded standard reference levels, indicating a potential risk of eutrophication. This may contribute to excessive algal growth, leading to oxygen depletion, loss of aquatic biodiversity, and disruption of fisheries and local livelihoods. Therefore, careful management should be considered to preserve the ecological health and economic significance of the Meghna estuary.

References

- [1] A. Robinson, Should we treat rivers as living things? *Nature* 643(8073) (2025), 901-903. doi: 10.1038/d41586-025-02263-w.
- [2] J. R. Karr, Defining and measuring river health, *Freshw. Biol.* 41(2) (1999), 221-234. doi: 10.1046/j.1365-2427.1999.00427.x.
- [3] S. Postel and B. Richter, Rivers for life: managing water for people and nature, *Choice Rev. Online* 41(7) (2004). doi: 10.5860/choice.41-4059.
- [4] J. Carstensen, M. Sánchez-Camacho, C. M. Duarte, D. Krause-Jensen and N. Marbà, Connecting the dots: responses of coastal ecosystems to changing nutrient concentrations, *Environ. Sci. Technol.* 45(21) (2011), 9122-9132. doi: 10.1021/es202351y.
- [5] X. Liu, J. Feng and Y. Wang, Chlorophyll a predictability and relative importance of factors governing lake phytoplankton at different timescales, *Sci. Total Environ.* 648 (2019), 472-480. doi: 10.1016/j.scitotenv.2018.08.146.
- [6] S. Chinthada and S. Bandla, Studies on seasonal variations in primary productivity and related water quality parameters in freshwater fishponds in coastal Andhra Pradesh, India, *Glob. J. Res. Anal.* (2021), pp. 17-21, doi: 10.36106/gjra/7409639.
- [7] N. P. Hemasankari, N. D. Prema, N. Kaladaran and V. Kripa, Seasonal variations of hydrographic parameters off the Chennai coast, India, *Ecol. Environ. Conserv.* 29(1) (2023), 374-380. doi: 10.53550/eec.2023.v29i01.056.
- [8] BIWTA, Bangladesh Inland Water Transport Authority, 2022.
- [9] S. Akter, M. Kamrujjaman and M. R. Islam, Assessment of physical parameters of water of the Dhaleshwari river in Bangladesh before setting up tanneries, *Sci. Res. J. SCIRJ* 7(5) (2019), 2201-2796.

- [10] N. Tasnim, Mst. A. Sultana, K. Tabassum, Md. J. Islam and M. Kunda, A review of the water quality indices of riverine ecosystem, Bangladesh, *Arch. Agric. Environ. Sci.* 7(1) (2022), 104-113. doi: 10.26832/24566632.2022.0701015.
- [11] F. Parvin, M. M. Haque and S. M. Tareq, Recent status of water quality in Bangladesh: a systematic review, meta-analysis and health risk assessment, *Environ. Chall.* 6 (2022), pp. 100416. doi: 10.1016/j.envc.2021.100416.
- [12] Md. J. Uddin and Y.-K. Jeong, Urban river pollution in Bangladesh during last 40 years: potential public health and ecological risk, present policy, and future prospects toward smart water management, *Heliyon* 7(2) (2021), p. e06107. doi: 10.1016/j.heliyon.2021.e06107.
- [13] M. F. Hasan et al., Health risk and water quality assessment of surface water in an urban river of Bangladesh, *Sustainability* 13(12) (2021), pp. 6832. doi: 10.3390/su13126832.
- [14] J. Fahrenkamp-Uppenbrink, Watch out for river nutrient imbalances, *Science* 365(6454) (2019), p. 652.17-654, doi: 10.1126/science.365.6454.652-q.
- [15] J. Hasan et al., Outwelling of nutrients into the Pasur River estuary from the Sundarbans mangrove creeks, *Heliyon* 8(12) (2022), p. e12270. doi: 10.1016/j.heliyon.2022.e12270.
- [16] A. H. Kamal and M. S. Khan, Coastal and estuarine resources of Bangladesh: management and conservation issues, *Maejo Int. J. Sci. Technol.* 3 (2009), 313-342.
- [17] D. A. Padmavathi and D. Satyanarayana, Distribution of nutrients and major elements in riverine, estuarine and adjoining coastal waters of Godavari, Bay of Bengal., *Indian J. Mar. Sci.* 28 (1999), 345-354.
- [18] S. M. B. Rahaman et al., Nutrient dynamics in the Sundarbans mangrove estuarine system of Bangladesh under different weather and tidal cycles, *Ecol. Process.* 2(1) (2013), doi: 10.1186/2192-1709-2-29.
- [19] S. M. Rahaman et al., Seasonal nutrient distribution in the Rupsha-Passur tidal river system of the Sundarbans mangrove forest, Bangladesh, *Ecol. Process.* 3(1) (2014). doi: 10.1186/s13717-014-0018-5.
- [20] S. H. Sadi, M. Azam, J. Tasnim, M. M. Hoque, M. Ashifur and A. Moontahab, Assessing the water quality and its influence on the chlorophyll-a concentration in the Karnaphuli river estuary, Dhaka Univ. *J. Earth Environ. Sci.* 13(1) (2024), 91-104. doi: 10.3329/dujecs.v13i1.77579.
- [21] M. M. Uddin, S. R. Chowdhury, M. Zafar and M. U. Nessa, Temporal and spatial variation of dissolved nutrients in the lower Meghna river estuary, Bangladesh, *Khulna Univ. Stud.* (2007), pp. 117-124. doi: 10.53808/kus.2007.8.1.0709-1.
- [22] M. M. Uddin, M. Zafar and S. Chowdhury, Water, salt and nutrient flux through the lower Meghna River estuary, Bangladesh, 2014.
- [23] P. Rogers, Eastern water study: Strategies to manage flood and drought in the Ganges-Brahmaputra basin, Rep. Submitt. USAID Dhaka, 1989.
- [24] M. Y. Miah, M. M. Hossain, P. Schneider, M. M. H. Mozumder, S. J. Mitu and Md. M. Shamsuzzaman, Assessment of ecosystem services and their drivers of change under human-dominated pressure-the Meghna river estuary of Bangladesh, *Sustainability* 13(8) (2021), p. 4458, doi: 10.3390/su13084458.
- [25] E. A. Suter, M. I. Scranton, S. Chow, D. Stinton, L. Medina Faull and G. T. Taylor, Niskin bottle sample collection aliases microbial community composition and biogeochemical interpretation, *Limnol. Oceanogr.* 62(2) (2016), 606-617. doi: 10.1002/lno.10447.

- [26] F. D. Wilde, D. B. Radtke, J. Gibs and R. T. Iwatsubo, National field manual for the collection of water-quality data - selection of equipment for water sampling A2 ed., Vol. 9. U.S. Geological Survey Techniques of Water-resources Investigations, 1998.
- [27] D. E. Canfield, C. D. Brown, R. W. Bachmann and M. V. Hoyer, Volunteer lake monitoring: testing the reliability of data collected by the Florida LAKEWATCH program, *Lake Reserv. Manag.* 18(1) (2002), 1-9. doi: 10.1080/07438140209353924.
- [28] K. Salonen and J. Sarvala, Field manual for the determination of chlorophyll and primary production in lake Tanganyika research, 1995.
- [29] T. McGrath et al., A rare inter comparison of nutrient analysis at sea: lessons learned and recommendations to enhance comparability of open-ocean nutrient data, *Earth Syst. Sci. Data* 11(1) (2019), 355-374. doi: 10.5194/essd-11-355-2019.
- [30] N. M. Tzollas, G. A. Zachariadis, A. N. Anthemidis and J. A. Stratis, A new approach to indophenol blue method for determination of ammonium in geothermal waters with high mineral content, *Int. J. Environ. Anal. Chem.* 90(2) (2010), 115-126. doi: 10.1080/03067310902962528.
- [31] Skalar Analytical, Low level phosphate analysis on the San++ continuous flow analyzer, 2012. <https://www.skalar.com/news/low-level-phosphate-analysis-on-the-san-continuous-flow-analyzer>.
- [32] S. Becker et al., GO-SHIP repeat hydrography nutrient manual: the precise and accurate determination of dissolved inorganic nutrients in seawater, using continuous flow analysis methods, *Front. Mar. Sci.* 7 (2020), p. 581790. doi: 10.3389/fmars.2020.581790.
- [33] L. I. Gordon, J. C. Jennings, A. A. Ross and J. Krest, A suggested protocol for continuous flow automated analysis of seawater nutrients (phosphate, nitrate, nitrite and silicic acid) in the WOCE hydrographic program and the joint global ocean fluxes study, *Coll. Ocean. Atmospheric Sci. Or. State Univ.*, 1993.
- [34] J. C. F. de Winter, S. D. Gosling and J. Potter, Comparing the Pearson and Spearman Correlation Coefficients Across Distributions and Sample Sizes: A Tutorial Using Simulations and Empirical Data, 2024, doi: 10.48550/ARXIV.2408.15979.
- [35] D. F. Watson and G. M. Philip, A refinement of inverse distance weighted interpolation, *Geoprocessing*, 2(4) (1985), 315-327.
- [36] QS, Environmental Quality Standard, Bangladesh Gazette, registered nr. DA-1, Minist. Environ. Gov. Bangladesh, 1997.
- [37] J. R. Brett, Energetic responses of salmon to temperature, a study of some thermal relations in the physiology and freshwater ecology of Sockeye Salmon (*Oncorhynchus nerka*), *Am. Zool.* 11(1) (1971), 99-113. doi: 10.1093/icb/11.1.99.
- [38] H. O. Portner and A. P. Farrell, ECOLOGY: physiology and climate change, *Science* 322(5902) (2008), 690-692. doi: 10.1126/science.1163156.
- [39] P. B. Moyle and J. J. Cech, *Fishes : An Introduction to Ichthyology*, 5th ed. Pearson Prentice Hall, 2004.
- [40] R. J. Davies-Colley and D. G. Smith, Turbidity suspended sediment, and water clarity: a review, *J. Am. Water Resour. Assoc.* 37(5) (2001), 1085-1101. doi: 10.1111/j.1752-1688.2001.tb03624.x.
- [41] Md. M. Shamsuzzaman, M. M. Islam, N. J. Tania, Md. Abdullah Al-Mamun, P. P. Barman and X. Xu, Fisheries resources of Bangladesh: present status and future direction, *Aquac. Fish.* 2(4) (2017), 145-156. doi: 10.1016/j.aaf.2017.03.006.

- [42] H. J. Patel and R. T. Vashi, Use of Naturally Prepared Coagulants for the Treatment of Wastewater from Dyeing Mills, Elsevier EBooks, 2015, pp. 147-158. doi: 10.1016/b978-0-12-802326-6.00006-x.
- [43] K. Sadhwani, T. I. Eldho, M. K. Jha and S. Karmakar, Effects of dynamic land use/land cover change on flow and sediment yield in a monsoon-dominated tropical watershed, *Water* 14(22) (2022), p. 3666. doi: 10.3390/w14223666.
- [44] Md. S. Islam and N. T. Meghla, Investigation on water quality in the Ashulia beel, Dhaka, *J. Fish. Res.* 14(1-2) (2010), 55-64.
- [45] S. Sharoni and I. Halevy, Weathering controls on the Phanerozoic phosphate cycle, *Res. Sq. Res. Sq.* 2021. doi: 10.21203/rs.3.rs-618748/v1.
- [46] D. Conley, C. Schelske and E. Stoermer, Modification of the biogeochemical cycle of silica with eutrophication, *Mar. Ecol. Prog. Ser.* 101 (1993), 179-192. doi: 10.3354/meps101179.
- [47] D. J. Randall and T. K. N. Tsui, Ammonia toxicity in fish, *Mar. Pollut. Bull.* 45(1-12) (2002), 17-23. doi: 10.1016/s0025-326x(02)00227-8.
- [48] E. B. Barbier, S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier and B. R. Silliman, The value of estuarine and coastal ecosystem services, *Ecol. Monogr.* 81(2) (2011), 169-193. doi: 10.1890/10-1510.1.
- [49] D. L. Breitburg, D. W. Hondorp, L. A. Davias and R. J. Diaz, Hypoxia, nitrogen, and fisheries: integrating effects across local and global landscapes, *Annu. Rev. Mar. Sci.* 1(1) (2009), 329-349. doi: 10.1146/annurev.marine.010908.163754.
- [50] F. J. Millero, *Chemical Oceanography*, CRC Press, 2016.
- [51] R. J. Diaz and R. Rosenberg, Spreading dead zones and consequences for marine ecosystems, *Science* 321(5891) (2008), 926-929. doi: 10.1126/science.1156401.
- [52] V. H. Smith, Eutrophication of fresh water and coastal marine ecosystems a global problem, *Environ. Sci. Pollut. Res.* 10(2) (2003), 126-139. doi: 10.1065/espr2002.12.142.
- [53] J. E. Cloern, Turbidity as a control on phytoplankton biomass and productivity in estuaries, *Cont. Shelf Res.* 7(11-12) (1987), 1367-1381. doi: 10.1016/0278-4343(87)90042-2.
- [54] J. B. Holman and D. G. Wareham, COD, ammonia and dissolved oxygen time profiles in the simultaneous nitrification/denitrification process, *Biochem. Eng. J.* 22(2) (2005), 125-133. doi: 10.1016/j.bej.2004.09.001.